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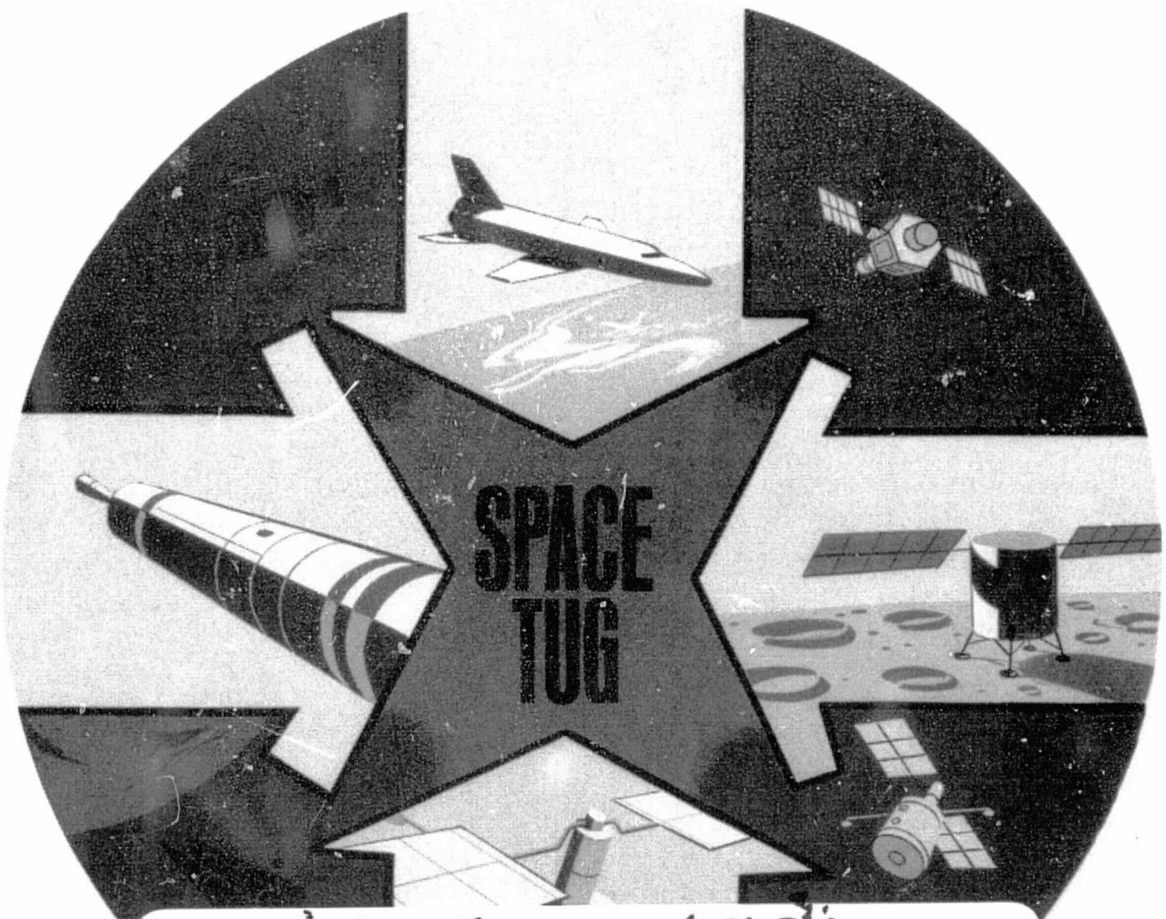

FINAL REPORT

Pre-Phase A Study for an Analysis of a Reusable Space Tug

VOLUME 2
TECHNICAL SUMMARY

Space Division
North American Rockwell

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TECHNICAL SUMMARY

MARCH 22, 1971

APPROVED BY

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Reusable Space Tug

Space Division
North American Rockwell

FOREWORD

This volume presents a technical summary of the results of the Pre-Phase A Study for an Analysis of a Reusable Space Tug. This study was conducted by the Space Division of North American Rockwell, Seal Beach, California, for the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas. Other volumes composing this final report include:

- Volume 1. Management Summary
- Volume 3. Mission and Operations Analysis
- Volume 4. Spacecraft Concepts and Systems Design
- Volume 5. Subsystems
- Volume 6. Planning Documents

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INTRODUCTION

The introduction of the Integrated Program Plan (IPP) by NASA and the President's Space Task Group in the fall of 1969 represents a significant milestone in space planning. An analysis of this plan shows at least three normalizing characteristics of the hardware elements required to satisfy the plan:

1. Commonality. To reduce overall space costs, hardware must be made common to mission areas (earth orbit, lunar, and planetary) and user agencies (NASA and DOD) and must maximize use of common subsystems (e.g., auxiliary propulsion system, electrical power system, and guidance and navigation) and of components (e.g., engines and fuel cells).

2. Reusability. To further reduce costs, hardware must, once developed, have the capability of being reused many times without significant refurbishment cost or operational complexity and with no degradation of mission reliability.

3. Flexibility. To assure rapid response to new mission requirements, hardware must be flexible enough to grow or be combined with other available hardware to satisfy requirements that are not and cannot be fully defined at this time. In addition, it must be able to function effectively even if some hardware elements are removed from the space inventory.

These characteristics must be developed at a minimum cost.

An earth orbital shuttle is being designed to fulfill these objectives for low earth orbital mission. Extension of reusable and flexible space systems beyond low earth orbit requires a space tug system. The space tug presents particularly difficult design problems, because it must (1) interface with virtually every other space hardware element — earth orbital shuttle, earth and lunar space stations, lunar surface base, propellant depots, experiment modules and satellites, and the translunar shuttle; (2) operate in all mission areas — low earth orbit, geosynchronous earth orbit, lunar, and unmanned planetary; and (3) perform for all user agencies, including NASA and DOD.

This nine-month pre-Phase A Study of a Reusable Space Tug is very timely in providing an identification of the space tug mission and design

requirements and providing the feasibility of a single modular concept in accomplishing the large spectrum of candidate missions.

The modular approach was selected with the goal of accomplishing a maximum number of missions with a minimum penalty to all missions, particularly those occurring most frequently. Figure 1 depicts the basic elements (crew module, cargo module, intelligence module, and propulsion module) along with ancillary kits and examples of combinations and modes to satisfy mission requirements.

This pre-Phase A study was conducted to determine the characteristics of such a system and its ability to satisfy effectively the broad mission requirements. The study was accomplished in two phases. The first phase concentrated on mission and system requirements. It also resulted in the parametric analysis of several modes of mission accomplishment and modular system approaches. The Phase I studies resulted in the selection of three concepts for more detailed mission, operations, economic, and conceptual studies during the second phase.

This report presents a detailed summary of the study results, and the presentation is separated into discussions of Phase-I and Phase-II study results. Conclusions arising from the study are then presented. Finally, conceptual approaches and additional study recommendations are discussed.

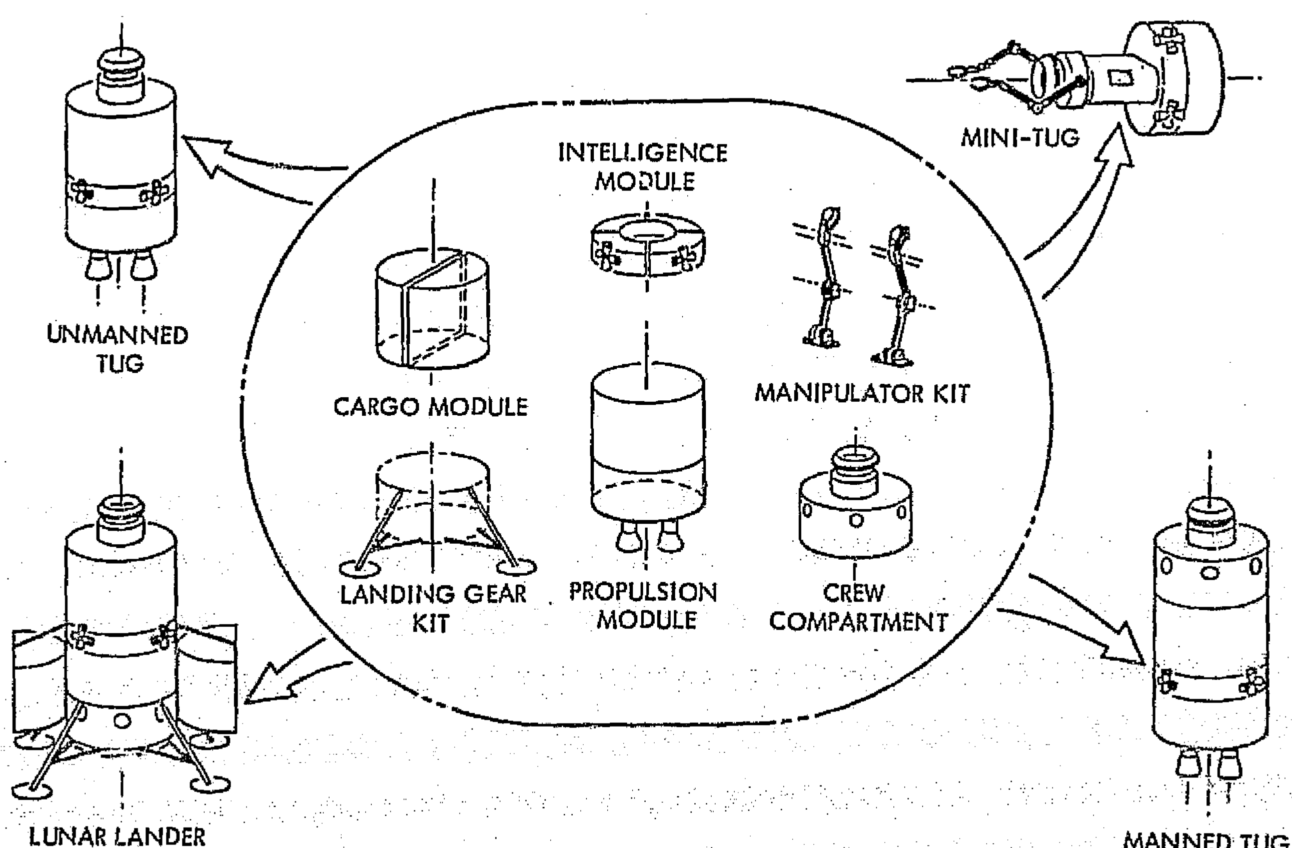


Figure 1. Space Tug Modules and Functions

BACKGROUND

OBJECTIVES AND SCOPE

The primary objective of this study was to determine the feasibility of a single, modular space tug design to effectively accomplish a broad spectrum of integrated program plan (IPP) missions. Another important objective was to determine the space tug mission interfaces and requirements, operational modes, system requirements, hardware interfaces, and technology implications.

Other objectives were to:

1. Determine the best subsystems and vehicle concept candidates through missions and operations analyses and design tradeoff studies
2. Determine the penalties in each mission arena for a single space tug design
3. Determine the capabilities and limitations of the conceptual vehicle designs in supporting the proposed missions and space tug and IPP objectives
4. Achieve results of sufficient detail that a comprehensive Phase A study could be initiated immediately with the final study documentation, should NASA so desire
5. Provide the necessary management planning information that would include preliminary design, fabrication, test, and operating schedule data plus key decision points, development risks information, and cost data

The scope of the study encompassed the following:

1. Establishment of candidate multipurpose approaches
2. Determination of mission and system interfaces and requirements
3. Development of program buildup data and economic tradeoffs

4. Conceptual design and subsystems analysis

5. Selection of up to three concepts for a conceptual design refinement study

6. Preparation of planning data for future program phases

APPROACH AND SCHEDULE

The overall approach to this study is shown in Figure 2. The study end products comprise a definition of the feasibility of the space tug concept, recommended conceptual space tug approaches and modes for accomplishing the missions, and planning documents that describe subsequent space tug program phases.

This study is separated into two phases, the first phase resulting in the designation of up to three concepts for a more detailed analysis during the second phase. Important initial inputs to the first phase studies were the NASA-designated mission models. Preliminary analysis of these models was conducted in both the mission and operations area and the conceptual areas to define several candidate multipurpose approaches. These

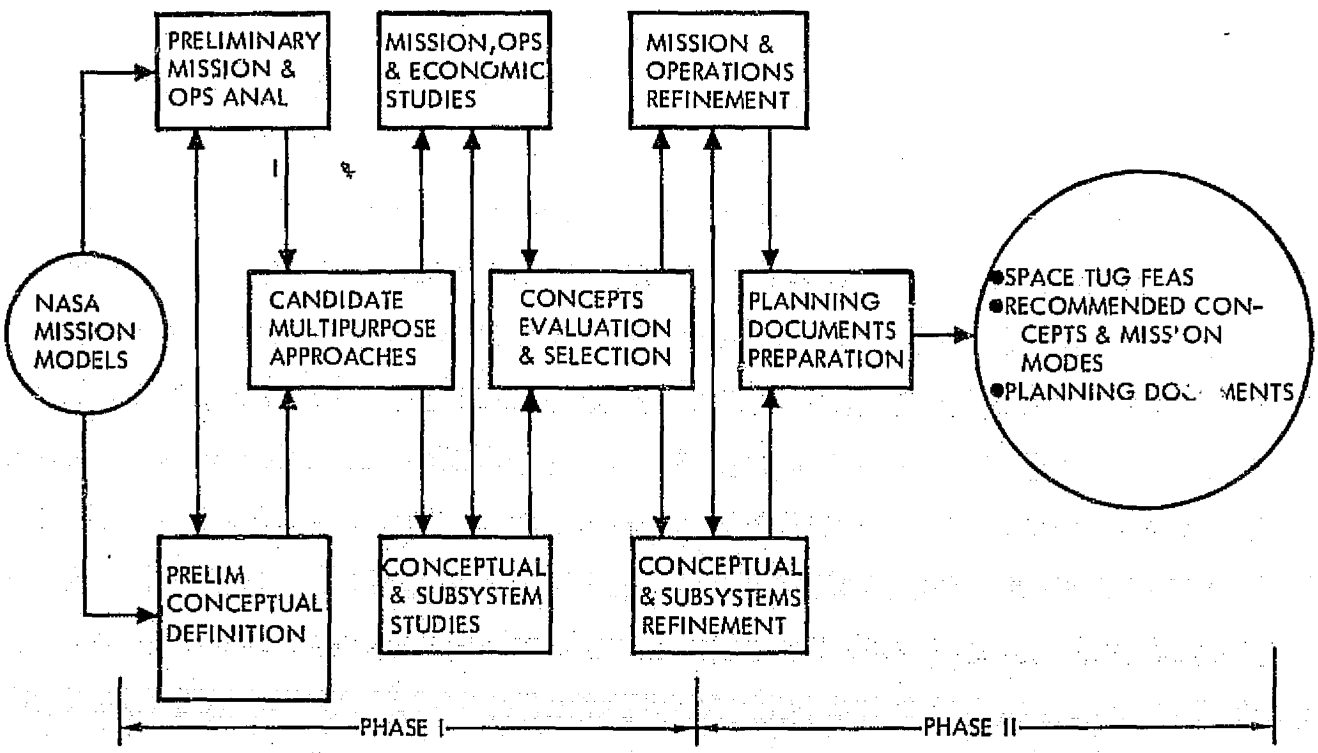


Figure 2. Study Logic

approaches and the candidate mission modes were submitted to mission, operations, and conceptual analysis to obtain data for evaluation and selection of up to three concepts. This report summarizes results of these Phase I studies and the resulting evaluation and selection of space tug concepts and provides a detailed description of the Phase II analyses. The Phase II studies concentrated on: mission, operations, and design refinement for the three selected space tug concepts; on certain key issues related to the comparative feasibility of the space tug and other potential approaches to mission accomplishment; and on the preparation of planning documents that describe preliminary plans for design, development, manufacturing, testing, and operations as well as program funding and a matrix of critical space tug decision points.

The study schedule is presented in Figure 3. The study was initiated on 8 June 1970, and all technical work was completed at the end of January 1971. The study comprised the four basic tasks shown on the figure. Three concepts for refinement studies were selected following an evaluation in October 1970; and the results of the Phase I studies were presented at the midterm briefing on 16 October 1971.

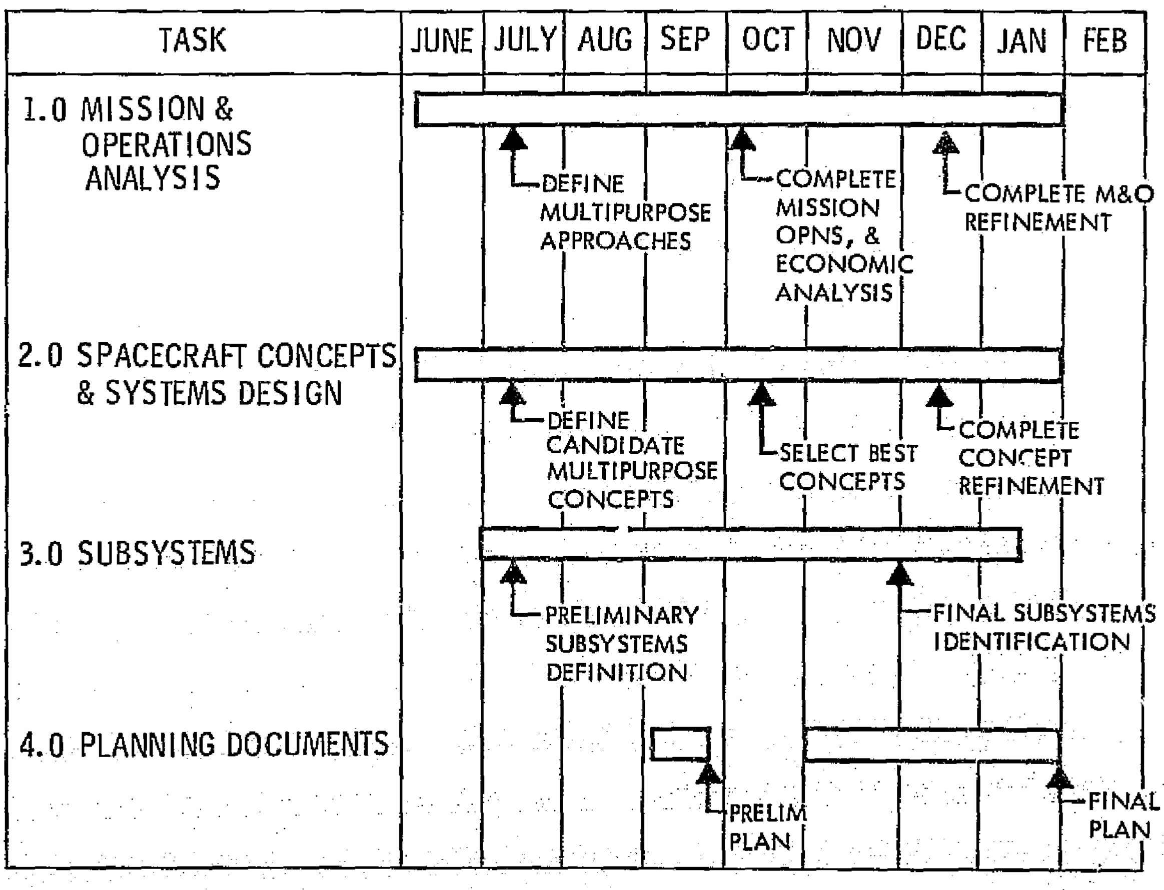


Figure 3. Study Schedule

STUDY GUIDELINES

The following summarize the most important guidelines employed during the study:

1. Space-based concept
2. Maximum autonomy
3. NASA-provided mission model and tug IOC dates
4. NASA-provided earth orbital shuttle (EOS) payload capability, payload dimensional constraints, and cost per flight
5. Multipurpose, modular tug concept
6. Compatibility with EOS launch constraints
7. Refuelable in earth and lunar orbits
8. Capability of integral use with the nuclear shuttle
9. Capability of manned or unmanned flight
10. Capability of quiescent status up to 180 days
11. Reusable at least 10 times or a lifetime of three years
12. Utilization of neuter docking devices
13. LO_2/LH_2 propellants

During the study, the influence on the space tug of varying many of these guidelines was determined; and where appropriate, deviations from these guidelines were introduced into the baseline space tug concepts. Sensitivity studies conducted as deviations from these guidelines included:

1. Ground basing
2. Varying degrees of autonomy
3. Variations in the mission model
4. Variations in EOS payload capability and cost per flight
5. Varying degrees of intelligence module modularity
6. Variations in the number of reuses
7. Utilization of other than neuter docking devices

PHASE I SUMMARY

This portion of the technical summary presents the highlights of the first phase of the study that resulted in the selection of three concepts for mission, operations, and design refinement studies during the second phase. This portion of the report is organized as follows:

1. Phase I Studies. Describes the studies performed during the first phase of the study

2. Mission Model. Describes the mission model utilized as a basis for the space tug study

3. Multipurpose Approach Matrix. Introduces the matrix of concepts for each major module that was formed to initiate the studies

4. Basic System Requirements. Presents the basic design requirements for the modules

5. Concepts Evaluation. Compares the overall effectiveness of the several concepts in accomplishing the planned missions

6. Phase I Recommendations. Presents the recommendations resulting from the Phase I studies

PHASE I STUDIES

Figure 4 describes in greater detail the key studies accomplished during the first phase. Selection of the several multipurpose concepts was the result of studies in both the mission and operations area and the conceptual area. The NASA mission models were analyzed to determine the various mission modes that may be employed to conduct the missions; the modules and staging modes that are necessary for each approach were defined; and the basic mission requirements were established. Preliminary performance data were generated on a rubber-vehicle basis to determine performance requirements for each mission mode and conceptual approach. System data for these studies were generated by conducting preliminary concepts-synthesis studies which were supported by preliminary subsystems, and mass properties analyses. As a result of these preliminary studies, several candidate multipurpose approaches were selected.

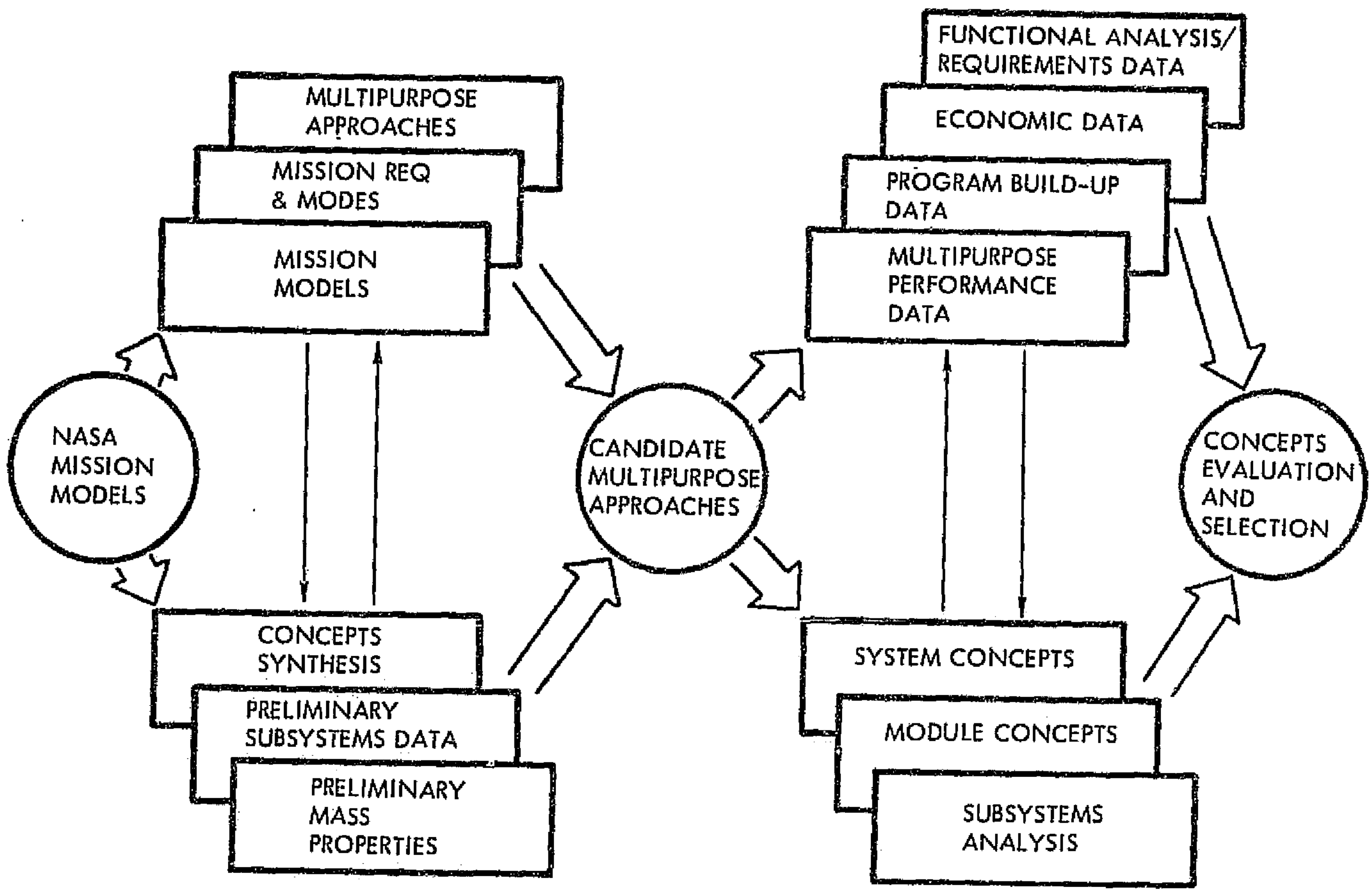


Figure 4. Phase I Studies

These approaches were submitted to mission, operations, and conceptual analyses to select up to three concepts for the second phase studies. Sufficient conceptual study was conducted to support the mission and operations studies and to determine the feasibility of the various conceptual approaches. Each of the multipurpose approaches were analyzed to develop off-loaded performance data for all of the missions. The mission models were further analyzed to develop the data necessary to establish the approach to building up the necessary space tug systems and to determine the propellant resupply cycles for the earth orbital shuttle and the cislunar shuttle. This model also describes the mission segments for each mission area. These data were the key elements for conducting an economic analysis (including analysis of a baseline mission model and variations to this model) for each multipurpose approach.

A functional analysis was also conducted for these missions to establish the space tug interfaces with other IPP systems and to define the basic requirements influencing the design of the space tug modules, constraints on their integration, and basic subsystem requirements.

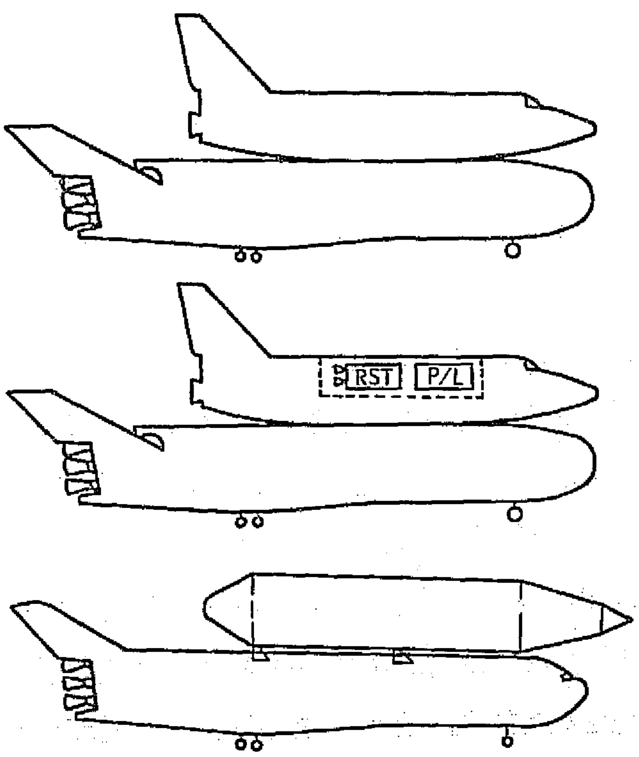
The data generated in these studies was then analyzed and concepts were selected for the second phase studies.

MISSION MODEL

The space transportation system envisioned to support unmanned and manned space activities in the future will feature system reusability to reduce mission costs, to provide mission flexibility with a minimum of systems, and to provide space capabilities which are not possible with current expendable systems. These systems are illustrated in Figure 5.

The earth orbital shuttle, comprised of a recoverable booster and a recoverable orbiter provides the capability for conducting manned operations, experiment module placement, and delivery of orbital cargo to low earth orbit. The reusable space tug will be designed to fit into the cargo bay of the earth orbital shuttle and will extend the regime of reusability beyond low earth orbit for manned and unmanned missions.

A cislunar shuttle could be employed for transport of large payloads between earth and lunar orbits. One possible approach is to combine the functions of an orbital injection stage used in place of the orbiter for the placement of large payloads in low earth orbit and the cislunar shuttle. After use as an injection stage, the vehicle may possibly be reused in orbit and refueled by the earth orbital shuttle.



LOW COST SYSTEM FOR:
- MANNED FLIGHT
- EXPERIMENT MODULES
- LOW EARTH ORBIT UNMANNED PAYLOADS
- ORBITAL CARGO

- EARTH ORBIT SUPPORT MISSIONS
- LOW COST DELIVERY OF SYNCHRONOUS & PLANETARY PAYLOADS
- PAYLOAD RETRIEVAL & REPAIR
- MANNED LUNAR LANDING CAPABILITY

- LOW COST DELIVERY OF LARGE PAYLOADS:
  - SPACE STATION MODULES
  - PROPELLANT
- POTENTIAL CIS-LUNAR SHUTTLE CAPABILITY

Figure 5. Space Transportation System

Figure 6 illustrates the overall regimes of reusability and the systems envisioned to provide this capability. The earth orbital shuttle provides reusability for low earth orbit missions. The space tug extends this region of reusability to high earth orbit, to lunar orbit and surface, and to the inner and outer planets. A chemical or nuclear cislunar shuttle may provide transportation between earth and lunar orbits.

The space tug will be economically capable of conducting all earth orbital missions beyond the low altitude capability of the earth orbital shuttle, including geosynchronous missions. It can also inject payloads to Mars, Venus, and Mercury and be recovered for reuse in a low earth orbit. Outer planet missions would require the expenditure of a space tug.

The space tug together with the cislunar shuttle provides reusable manned lunar mission capability. Although primary logistics between earth and lunar orbit may be accomplished by the cislunar shuttle, the space tug can transport men in one direction between earth orbit and lunar orbit under normal conditions. The space tug has the inherent capability for providing rescue and abort capability for lunar surface and orbit operations. Logistics missions between lunar orbit and surface are accomplished by the space tug.

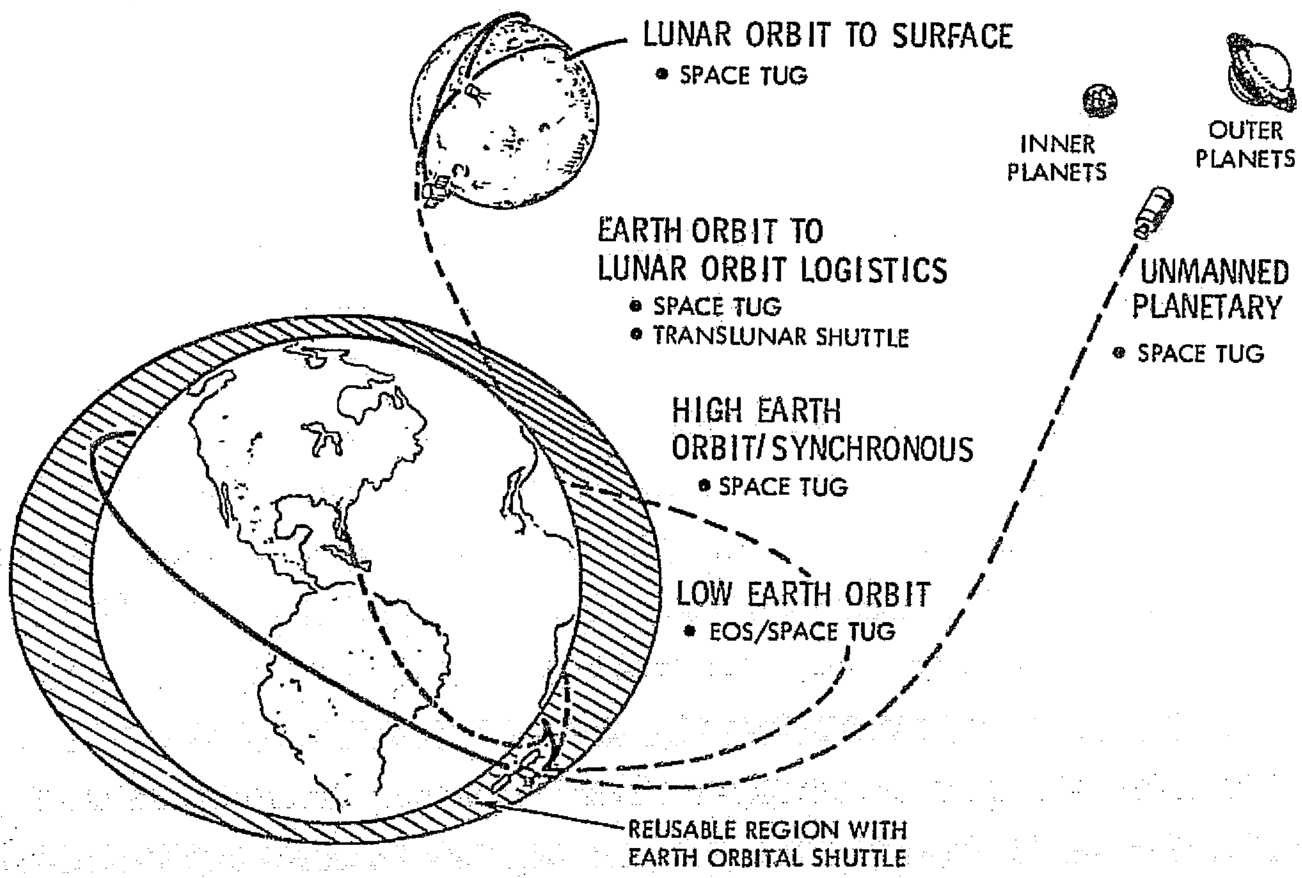


Figure 6. Space Reusability Regimes

Low Earth Orbit Missions

The categories of missions for the space tug in low earth orbit are summarized in Figure 7. Although the earth orbital shuttle can conduct low earth-orbit missions, use of the space tug, in conjunction with the shuttle, improves operational flexibility and economy. Satellite delivery, retrieval, servicing, and repair require that the space tug inimately interface with the satellites. The space tug also will be used in the assembly of the space station and for station keeping operations with the space station and cislunar shuttle. The space tug can also increase the net payload delivered by the earth orbital shuttle by functioning as a space-based stage that transfers payloads between an earth orbital shuttle at 100 nautical miles (185 km) and the space station at 270 nautical miles (500 km).

Missions in this category are of high frequency when compared to other missions, particularly when transfer of payloads and servicing of space station satellites are considered.

Geosynchronous Missions

The large number of satellites which are required to be placed in geosynchronous orbits along with the high characteristic velocity for accomplishing this mission from low earth orbit [14, 100 ft/sec (4. 3 km/sec) outbound delta-V] make this mission a key performance driver for the space

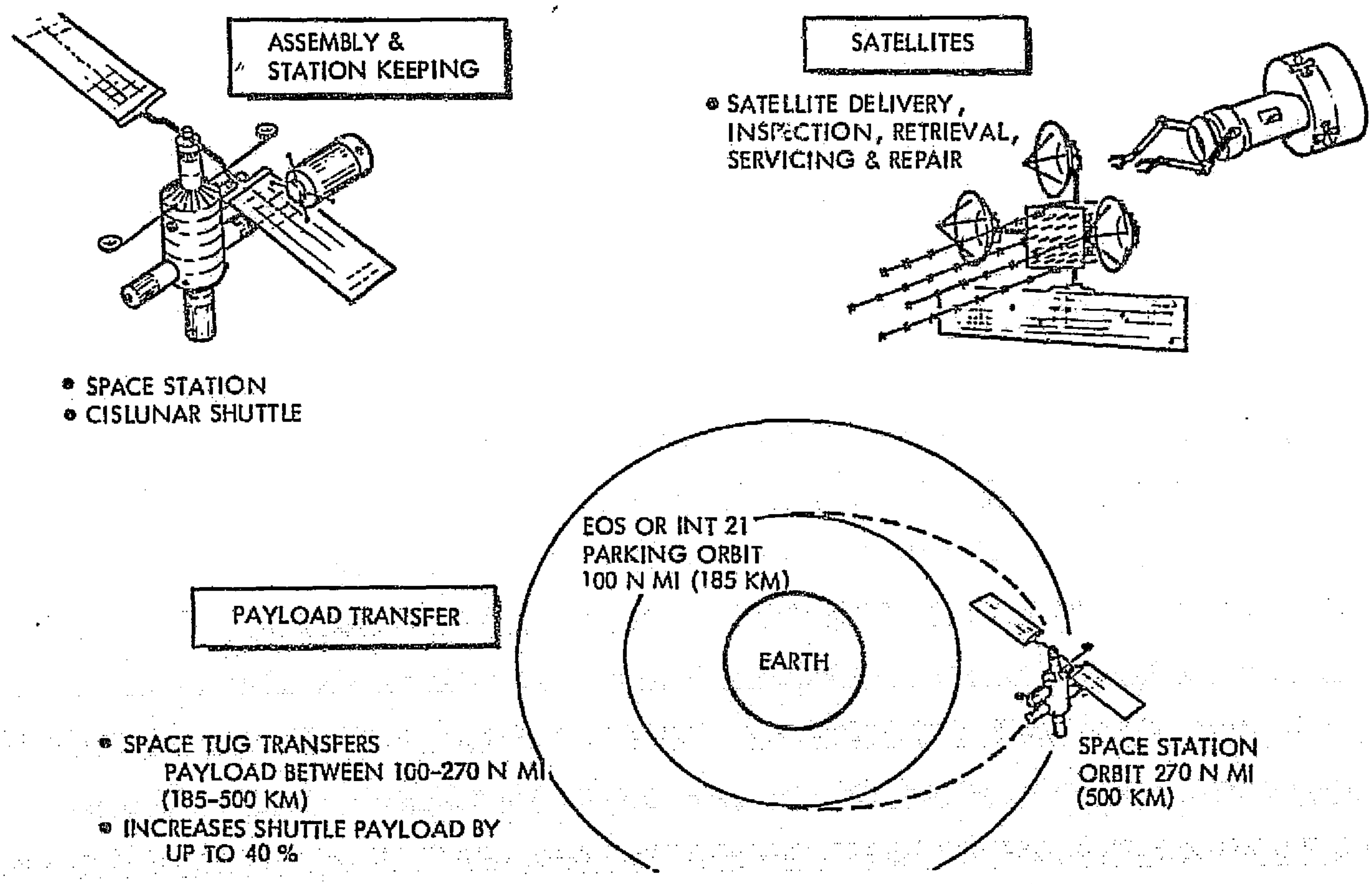
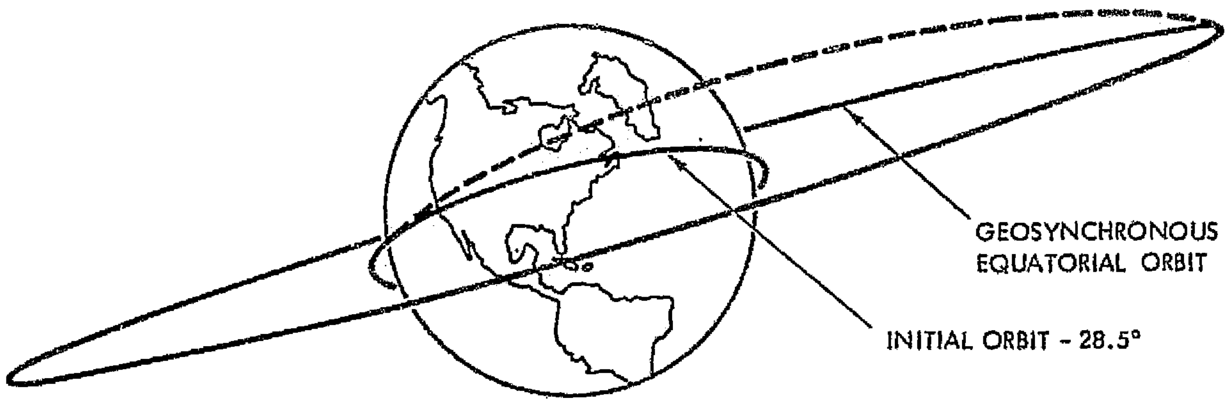


Figure 7. Low Earth Orbit Missions

tug concept (Figure 8). Fully recoverable space tug concepts for this mission include single stage and two-stage (equal size) space tugs for the delivery of payloads up to 10,000 pounds (4540 kg). Two-stage systems require about 41,000 pounds (18,600 kg) propellant per stage. A single-stage space tug is very sensitive to both specific impulse and stage mass fraction and between 60,000 pounds (27,000 kg) and 80,000 pounds (36,000 kg) of propellant are required to accomplish the mission. The characteristic velocity is minimized by conducting this mission from the lowest possible inclination which may be reached by the earth orbital shuttle, 28.5 degrees.



- HIGH FREQUENCY USAF & NASA MISSIONS
- PAYLOADS UP TO 10,000 LB (4540 KG)
- VERY SENSITIVE TO SPECIFIC IMPULSE & STAGE MASS FRACTION

Figure 8. Geosynchronous Missions

Lunar Operations

Figure 9 illustrates the tug missions involved in conducting lunar activities. Primary use of the space tug in lunar operations is for the delivery of payloads and crew between lunar orbit and the lunar surface. All modules of the space tug are required to conduct these operations.

Early lunar missions will be conducted by the space tug, prior to the placement of a lunar surface base, from an orbiting lunar station which is resupplied by the cislunar shuttle. During these missions, the space tug crew module will serve as a lunar surface shelter for 4 men for up to 28 days. Total payloads of up to 20,000 pounds (9100 kg) (including the shelter) would be carried to the surface and between 10,000 and 20,000 pounds (4540 and 9100 kg) would be returned to orbit.

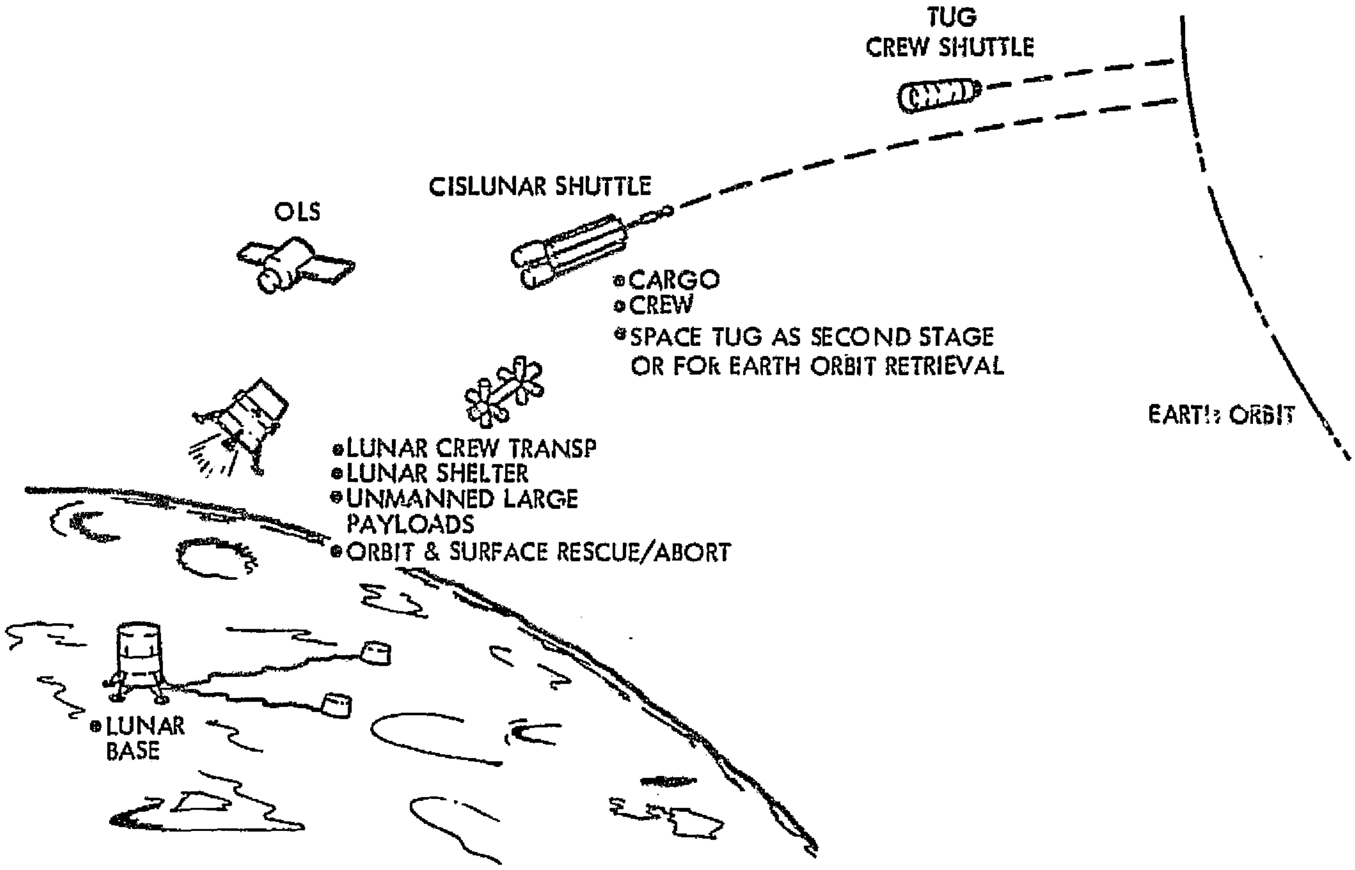


Figure 9. Lunar Operations

The space tug will also be used to deliver the lunar surface base modules to the surface. Because of their large mass, the tug would be expended in accomplishing this mission. During operation of the lunar surface base, the tug will provide logistics support, transporting crew and payload between the lunar orbiting space station and the surface base.

Two or more space tugs will be used in lunar operations; one for the logistics tasks previously described and the others for space station support and for mission safety. The space tug can change planes up to 90 degrees and return in lunar orbit, return to earth orbit, or descend to the surface and return with a moderate plane change, thus providing an inherent capability for rescue and abort in lunar operations.

In addition, the space tug may provide the capability of transporting crew and moderate cargo in one direction between earth and lunar orbit, or may be used to improve the efficiency of the reusable translunar nuclear or chemical shuttle as a second stage or as a stage that retrieves the translunar shuttles upon their return to an elliptical earth orbit.

Unmanned Planetary Missions

The unmanned planetary missions also require high performance. These missions are of low frequency compared to other space tug missions. Figure 10 describes the overall characteristics of these missions. Mars, Venus, and Mercury missions are accomplished by either a single-stage space tug or with a two-stage tug. A space tug having a propellant capacity of 80,000 pounds (36,300 kg) can inject approximately 54,000 pounds (24,500 kg) of payload in the two-stage mode or 13,000 pounds (5,900 kg) in a single-stage recovered mode. The outer planet missions are considerably more demanding, requiring an injection characteristic velocity of 24,000 to 26,000 ft/sec (7.3 to 7.9 km/sec). Accomplishment of this mission requires either a single-stage expended mode or a two-stage mode with expenditure of the second stage. If the space tug contains 80,000 pounds (36,300 kg) of propellant, approximately 8,000 pounds (3,630 kg) of payload can be injected in the single-stage mode and 23,000 pounds (10,400 kg) can be injected in the two-stage mode.

The space tug has a payload injection capability greater than those anticipated for future unmanned planetary missions. Payloads currently planned for the inner planet missions do not exceed 8,000 pounds (3600 kg)

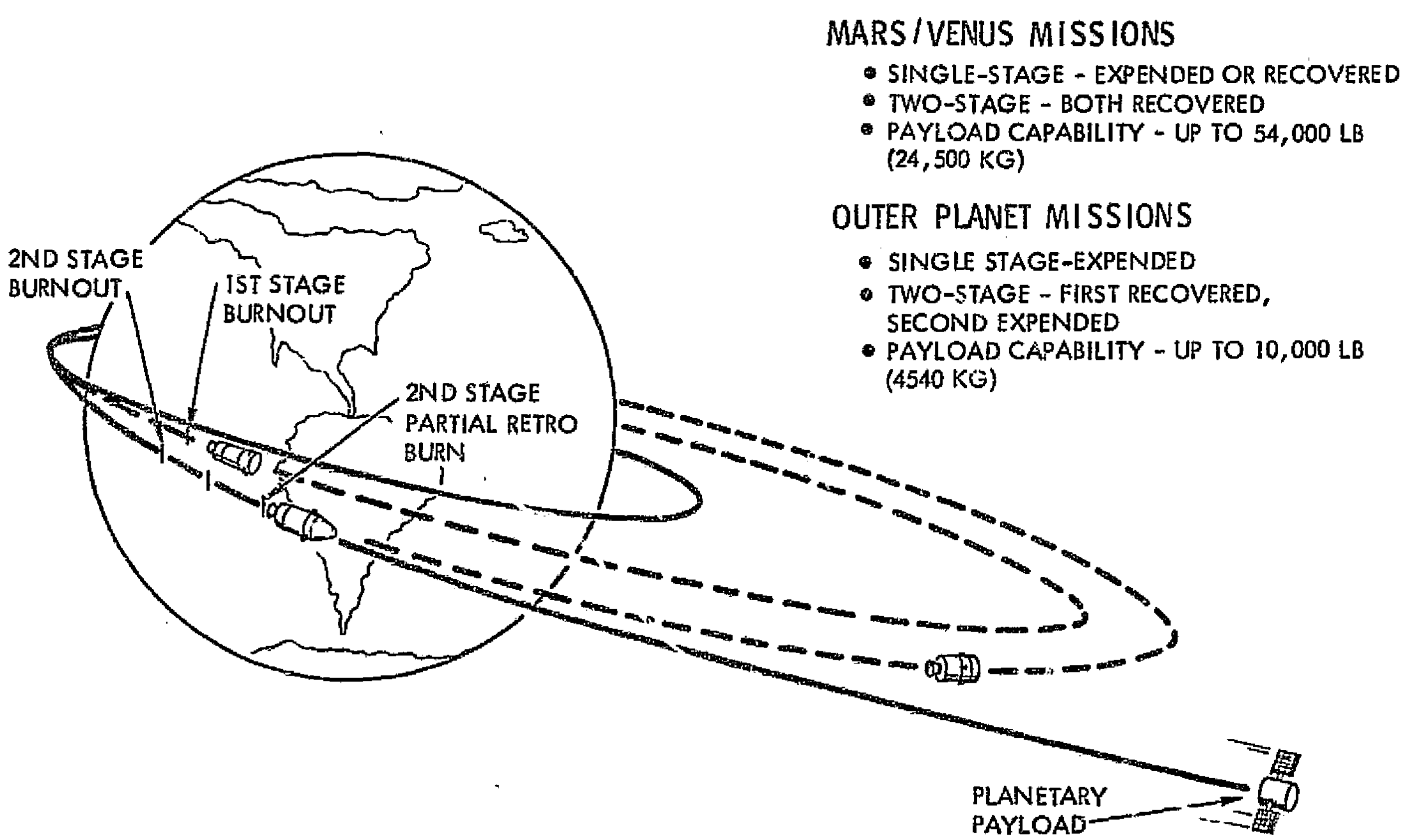


Figure 10. Unmanned Planetary Missions

and outer planet payloads are less than 2,000 pounds (900 kg). Because these payloads were apparently based on existing expendable booster capabilities, the additional capability of the space tug for these missions may lead to an upward revision of payload weights.

Overall Mission Model Characteristics

IOC dates for the integrated program plan systems used in this study are shown in Figure 11. The earth-orbital shuttle will be introduced early in 1978. An unmanned version of the space tug, comprised of the intelligence and propulsion modules, will be introduced about two years later to provide a capability for emplacement of payloads beyond the EOS orbital capability. Later, during 1980 and in conjunction with space station operations, the space-tug crew module would be introduced to allow manned operations for space station assembly and support. The entire tug capability will be developed by 1983 to support the lunar mission area. This will include the crew module modification to allow it to operate as a surface shelter and development of the landing legs and cargo module.

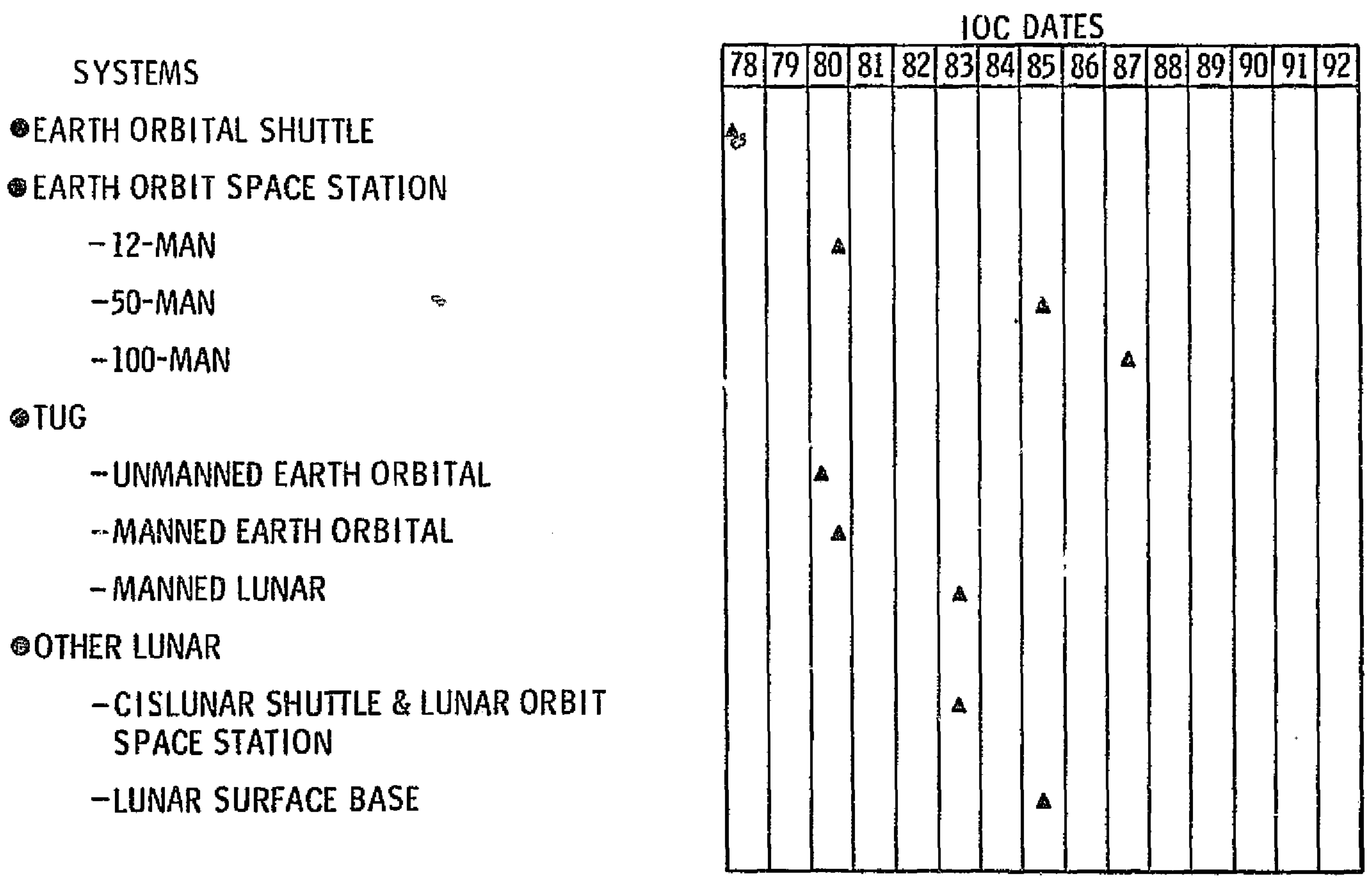


Figure 11. System IOC Dates

Figure 12 shows the number of space tug missions from 1980 to 1989 in the major categories of mission support:

1. Satellite placement, which includes unmanned satellite placement in earth orbit beyond EOS capability and to the near and far planets

2. Earth orbit space station support, which includes payload and crew transfer between the space station and EOS, experiment module maintenance, and space station assembly

3. Lunar program support, which includes propellant and payload transfer between the EOS and the cislunar shuttle in earth orbit, missions between the lunar orbit station and surface, and cislunar shuttle maneuvering in earth orbit

As indicated, most of the missions require only a low characteristic velocity for their accomplishment, these missions generally requiring the transport of relatively large propellant, cargo, or experiment modules between closely spaced low earth orbits such as between 100 and 270 nautical miles (185 and 500 km). Although the moderate to high characteristic velocity missions are comparatively low in frequency, they are significant because of the large amounts of propellant consumed in accomplishing these missions. They include geosynchronous and planetary payload insertions and lunar landing missions. The 43 missions shown for the geosynchronous

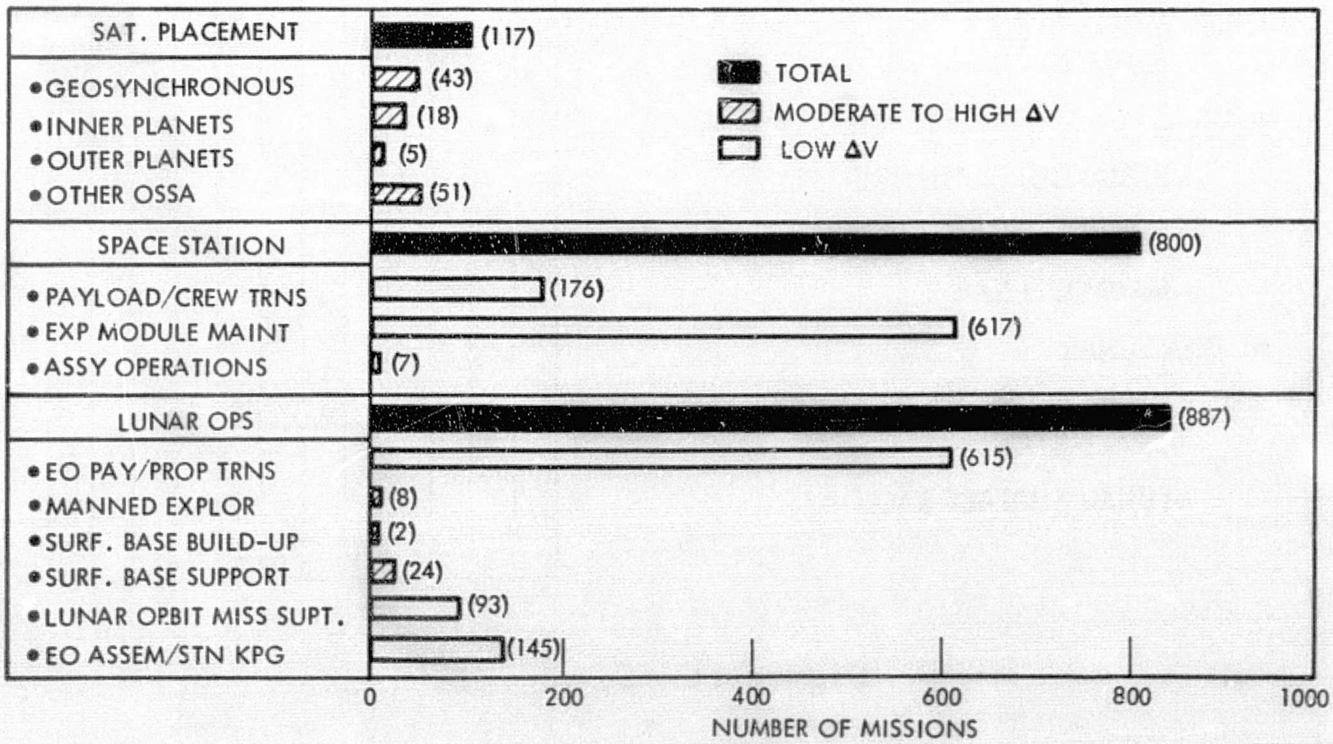


Figure 12. Space Tug Mission Frequency

category assume the capability for clustering multiple payloads. This is considered to be a lower boundary of missions, which could be as high as 140 if each payload was injected separately.

Figure 13 shows a plot of payload weight as a function of the outbound mission characteristic velocity. These data illustrate the broad range of mission requirements for the space tug. As shown, they vary from high payload weights (characteristic of a loaded reusable nuclear shuttle) at low characteristic velocities to relatively low payload weights at the high characteristic velocities associated with geosynchronous and planetary missions.

Also shown on this figure are the typical capabilities of a LO_2/LH_2 stage which contains 51,000 pounds (23,100 kg) of propellant and has a mass fraction of 0.850. Several staging modes are illustrated, including a single stage either recovered or expended, and two stages both recovered or the second expended. This illustrates, generally, the manner in which the entire mission model may be accomplished. Expenditure of the tug, in this case, is required only for the outer planet missions. Each space tug concept has a different capability, and staging modes in accomplishing the missions are primarily dependent upon the stage propellant loading.

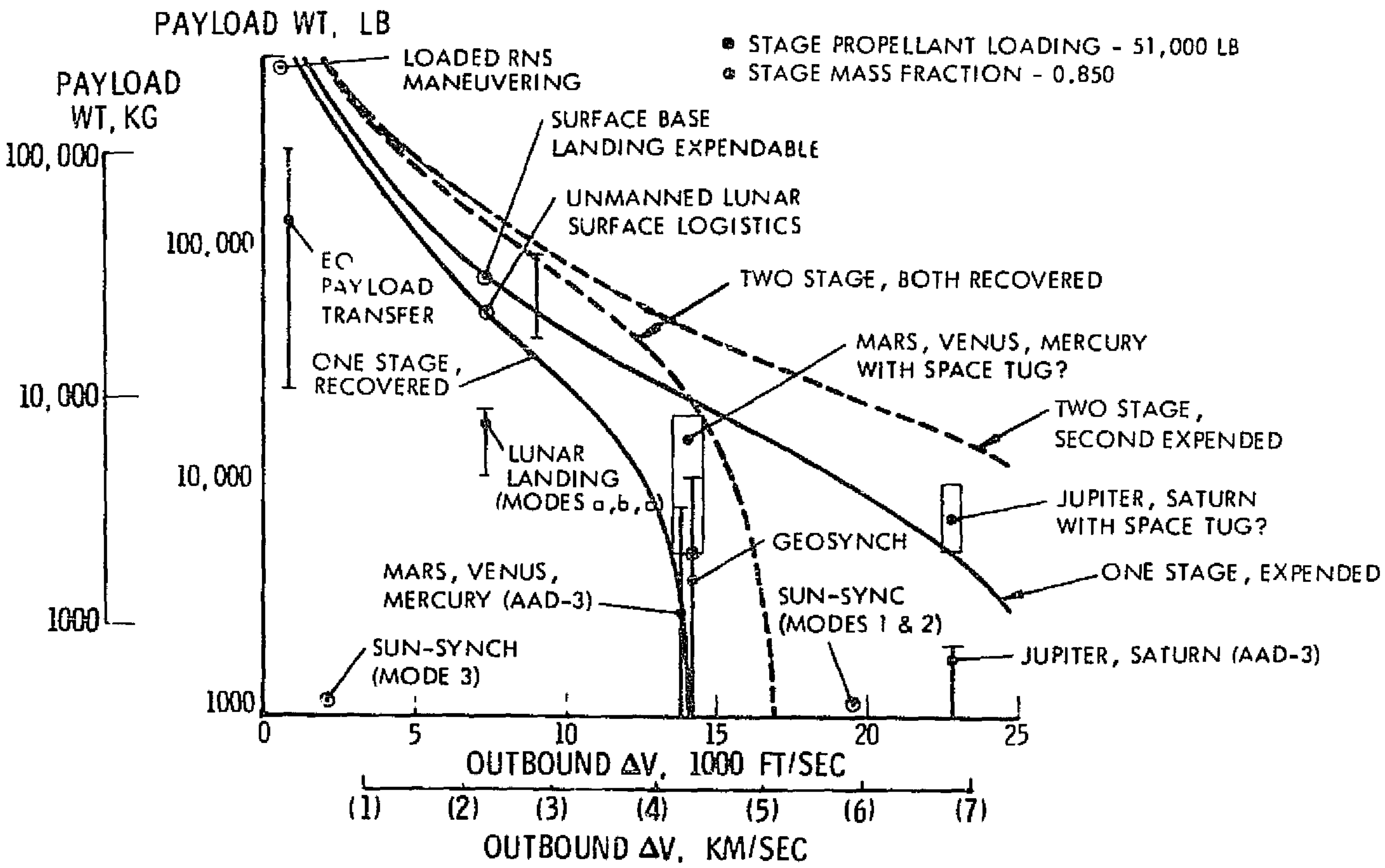


Figure 13. Space Tug Payload - Delta-V Map

As shown in Figure 14, most of the space tug missions require very low propellant loadings for their accomplishment. High frequency missions such as propellant and payload transfer between the EOS and space station, and near-space station experiment module support require less than 6000 pounds (2720 kg) of propellant for their accomplishment. Although there are many satellite emplacement missions to geosynchronous orbit and to the near and far planets which require large propellant loadings, they are relatively small in number compared to the low earth orbit support missions. Lunar landing missions also require large propellant loadings, but are infrequent compared to low earth orbit support missions.

While such data may tend to imply the requirement for more than one space tug because of two regions of maximum propellant loadings [near 6,000 pounds (2720 kg) and between 50,000 and 80,000 pounds (22,600 and 36,200 kg)], later data will indicate that the larger propulsion module is economically efficient for the low propellant-loading missions.

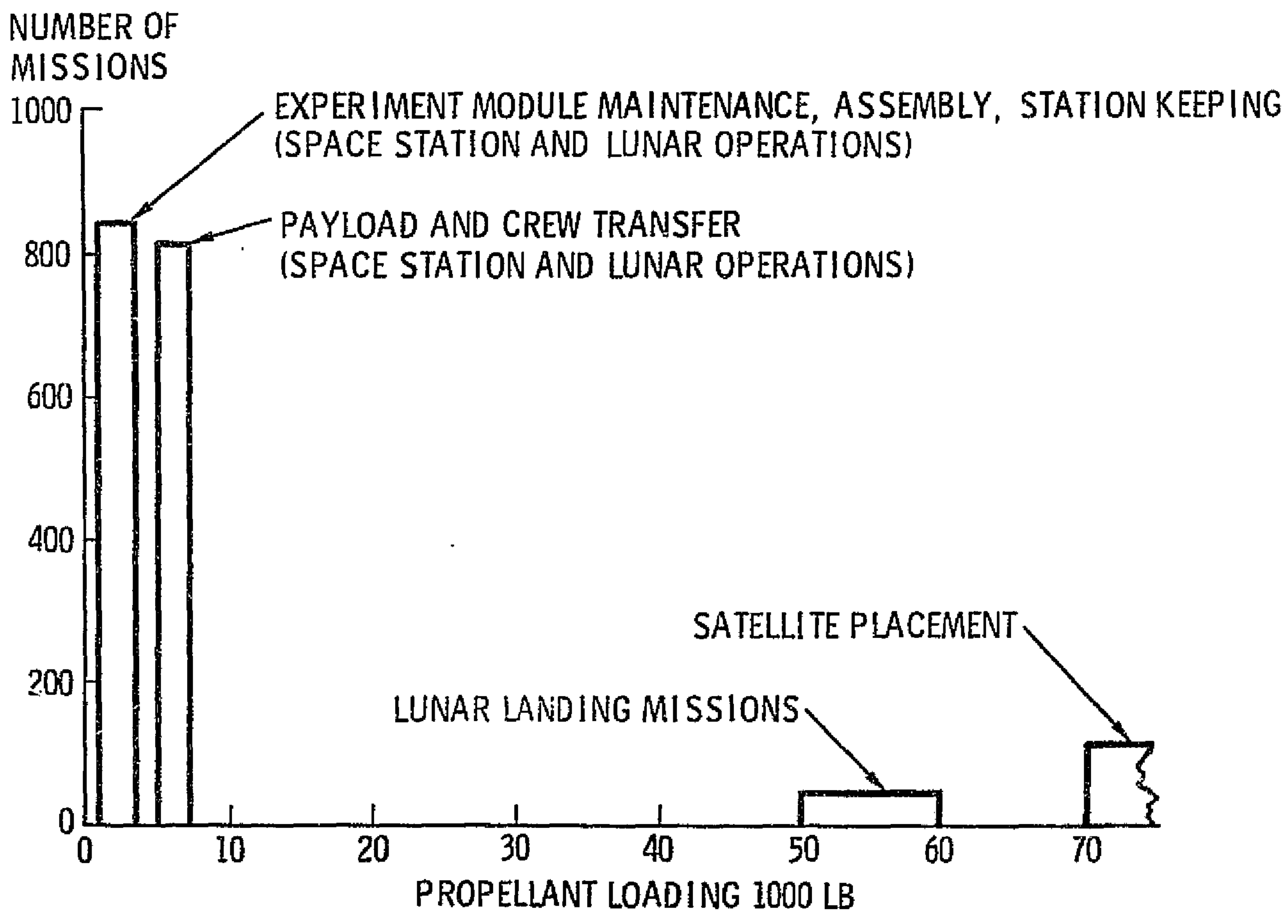


Figure 14. Propulsion Module Propellant Loading Frequency

MULTIPURPOSE APPROACH MATRIX

The overall methodology used to establish a matrix of concepts is illustrated in Figure 15. As was indicated in Figure 13, the space tug propulsion-module's maximum performance requirements are driven primarily by the geosynchronous and lunar landing missions. Design characteristics of this module should originate from one of these missions

MODULES	ORIGIN OF MODULE DESIGN	OTHER MISSION APPLICATIONS
PROP MODULE	SIZED FOR EITHER: • LUNAR LANDING • GEOSYNCHRONOUS	• OFF-LOAD • TWO STAGE • ADD TANK SETS • EXPEND STAGES OR TANKS
CREW MODULE	SIZED FOR: • 4 MEN/28 DAY LUNAR SHELTER OR 6 MEN/7 DAY CREW TRANSPORT	MODIFY INTERIOR ARRANGEMENT FOR: • 6-12 MEN FOR SHORT TIME • 2 MEN FOR SHORT TIME
INTELLIGENCE MODULE	SIZED FOR: • UNMANNED MISSIONS	PROVIDE CAPABILITY FOR ADDITION OF FUEL CELLS FOR MORE DEMANDING MISSIONS

Figure 15. Multipurpose Approach Methodology

and other missions may be accomplished by either utilizing two stage configurations or by off-loading propulsion module propellants.

The primary, driving, design condition for the crew module is the requirement to provide a lunar shelter for 4 men for up to 28 days or to transport 6 men between earth orbit and lunar orbit. Under emergency conditions arising from the lunar missions or in earth orbit, it should also be capable of providing life support for 6 to 12 men for a short period of time. Near-space station support missions and payload transfer missions between the EOS and space station or cislunar shuttle require only a two man crew. A crew module designed to the lunar shelter requirements is considerably over-sized for this mission.

The intelligence module will provide the capability of guidance, navigation, control, communications, system checkout and monitoring, power, attitude control, and low ΔV translational control. This system would be designed for the unmanned missions and the additional power required for manned missions would be added as a kit. Additional landing aids equipment for lunar landing would be added as kits.

Propulsion Module Matrix

Arrangements of propulsion modules that have been considered are shown in Figure 16. These include single stages, two tanden stages, a stage with a tank set, and parallel stages. These concepts may be either partially or totally expended in accomplishing some of the missions. Both stages of the two stage systems are of equal size. For the system comprised of a stage and tank set, two cases have been considered: (1) the tank set has the same propellant capacity as the stage and (2) the tank set and stage are of different propellant capacities.

Figure 17 presents the matrix of multipurpose concepts developed during the first month of the study. Ten concepts were originally devised, but concepts 9 and 10 (not shown) were incapable of accomplishing some of the missions and required expenditure of two stages on the high performance missions. Concept 11, comprised of a 9,000 pound (4,540 kg) capacity stage and a 48,000 pound (21,800 kg) capacity tank set, was developed toward the end of Phase I. This concept originates from the geosynchronous mission. The tank set is expended while emplacing a 10,000 pound (4540 kg) payload at geosynchronous conditions. The small stage and intelligence module return to low earth orbit for reuse.

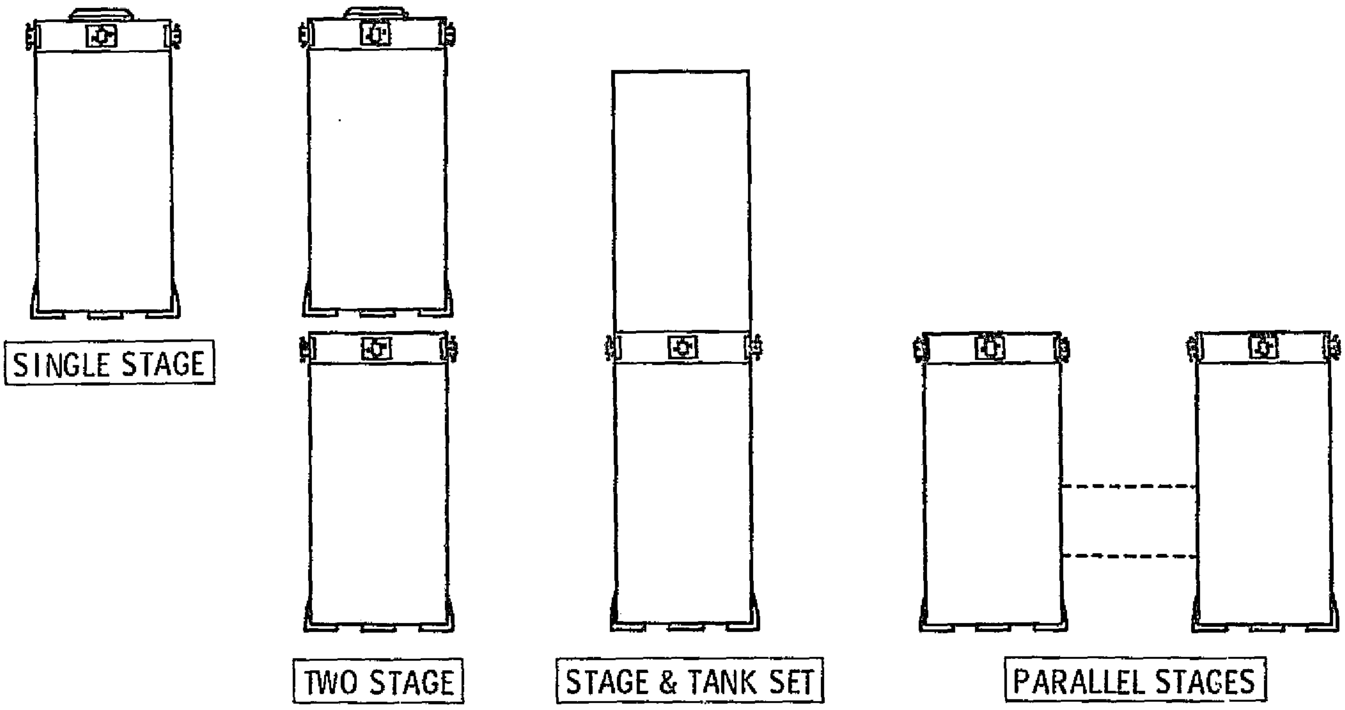


Figure 16. Propulsion Module Arrangements

CONCEPT	PROPELLANT LOADING, 1000 LB (1000 Kg)	STAGING ARRANGEMENTS				
		GEOSYNCH	LUNAR LANDING	LOW EARTH ORBIT	PLANETARY	
					INNER	OUTER
1	80 (36)	SINGLE STAGE	SINGLE STAGE	SINGLE STAGE	SINGLE STAGE	SINGLE STAGE
2	52 (24)	TWO STAGE OR STAGE & TS	SINGLE STAGE (MODE A)	SINGLE STAGE	TWO STAGE	SINGLE STAGE
3	45 (20)	STAGE & TS	STAGE & TS	SINGLE STAGE	TWO STAGE	TWO STAGE (SECOND EXP)
4	41 (19)	TWO STAGE	SINGLE STAGE (MODE B)	SINGLE STAGE	TWO STAGE	TWO STAGE (SECOND EXP)
5	36 (16)	TWO STAGE	SINGLE STAGE (MODES C & D)	SINGLE STAGE	TWO STAGE	TWO STAGE (SECOND EXP)
6	31 (14)	TWO STAGE (SECOND REC)	STAGE & TS	SINGLE STAGE	SINGLE STAGE	TWO STAGE (SECOND EXP)
7	27 (12)	SINGLE STAGE	STAGE & TS	SINGLE STAGE	SINGLE STAGE	TWO STAGE (SECOND EXP)
8	23 (10)	TWO STAGE (SECOND EXP)	STAGE & TS (MODES B, C, & D)	SINGLE STAGE	SINGLE STAGE	———
11	9/48 (4/22)	SMALL STAGE & TS (TS EXPENDED)	SMALL STAGE & TS (MODE A)	SMALL STAGE	SMALL STAGE & TS (TS EXPENDED)	SMALL STAGE & TS (BOTH EXPENDED)

MISSION FROM WHICH CONCEPT ORIGINATED   PARTIALLY OR FULLY EXPENDED IN ACCOMPLISHING MISSION

Figure 17. Propulsion Module Matrix

The stage LO_2/LH_2 propellant loadings vary from 80,000 pounds (36,200 kb) for concept 1 which originates from the geosynchronous mission to 23,000 pounds (10,400 kg) for a two-stage system originating from the geosynchronous mission (the second stage is expended while accomplishing this mission).

All of the concepts originated from either the geosynchronous or lunar landing mission. Three modes were considered for the lunar landing mission (Modes A, B, and C). Mode A required a 20,000 pound (9100 kg) round trip payload comprised of a crew module weighing about 10,000 pounds (4540 kg) and 10,000 pounds (4540 kg) of experiments, mobility devices, and expendables. Mode B required 20,000 pounds (9100 kg) to be delivered to the surface and 10,000 pounds (4540 kg) to be returned to orbit. Mode C required two surface sorties of 10,000-pound (4540-kg) roundtrip capability each for mission accomplishment. One tug carries the crew module and crew and the other carries the experiments, mobility devices, and expendables. Two-stage (tandem) operations were considered for the lunar mission, but were rejected because performance was reduced in this mode. Those lunar mission concepts which are shown as a stage and a tank set could alternatively be accomplished in a two-parallel stage mode.

Figure 17 shows the mission from which each concept originated, the staging relationship for each mission, and whether an expendable or recoverable mode is employed. As shown, the only concept that utilizes the same staging mode for all missions is concept 1 which is always a single stage configuration.

The performance of four space tug propulsion-module approaches are compared in Figure 18. The mission from which each concept originated is illustrated on this chart. The first concept originated from the lunar landing mission and has 52,000 pounds (23,600 kg) of propellant capacity. The second concept originates from a recoverable single-stage geosynchronous mission and has 80,000 pounds (36,200 kg) of propellant capacity. The third concept originates from a recoverable two stage (equal size) geosynchronous mission and has 36,000 pounds (16,300 kg) of propellant capacity per stage. A fourth concept, originating from the low earth-orbit support mission, is shown for reference in this mission category only. Because of its small propellant capacity, 5,000 pounds (2,260 kg), this concept cannot accomplish all of the space tug missions and, therefore it does not have multipurpose capability. The relative capabilities of these space tug concepts for the low earth orbit support mission [transfer of a 40,000 pound (18,100 kg) payload between 100 nautical miles and 270 nautical miles (185 and 500 km) is shown for reference], for placement

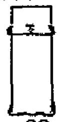
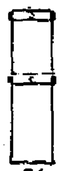
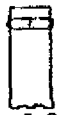
MISSION ORIGIN/ CONFIGURATION	MISSION PERFORMANCE COMPARISONS				
	LOW EO SUPPORT	SYNCH EQUATORIAL	LUNAR LANDING	NEAR PLANETS	OUTER PLANETS
LUNAR LANDING  W_{prop} = 52,000 LB	• SINGLE STAGE • $\frac{W_{pay}}{W_{prop}} = 6.2$	• 2-STAGE (BOTH REC) • $\frac{W_{pay}}{W_{prop}} = 0.13$	• SINGLE STAGE • $\frac{W_{pay}}{W_{prop}} = 0.38$	• 2-STAGE (BOTH REC) • W_{pay} = 26,000 LB	• 2-STAGE (2ND EXP) • W_{pay} = 12,000 LB
GEOSYNCHRONOUS  W_{prop} = 80,000 LB	• SINGLE STAGE • $\frac{W_{pay}}{W_{prop}} = 6.1$	• 1-STAGE (RECOV) • $\frac{W_{pay}}{W_{prop}} = 0.12$	• SINGLE STAGE • $\frac{W_{pay}}{W_{prop}} = 0.34$	• 2-STAGE (BOTH REC) • W_{pay} = 56,000 LB	• 2-STAGE (2ND EXP) • W_{pay} = 23,000 LB
GEOSYNCHRONOUS  W_{prop} = 36,000 LB	• SINGLE STAGE • $\frac{W_{pay}}{W_{prop}} = 6.3$	• 2-STAGE (BOTH REC) • $\frac{W_{pay}}{W_{prop}} = 0.13$	• 2-STAGE PARALLEL OR STAGE PLUS TANK SET • $\frac{W_{pay}}{W_{prop}} = 0.34$	• 2-STAGE (BOTH REC) • W_{pay} = 13,000 LB	• 2-STAGE (2ND EXP) • W_{pay} = 7,000 LB
LOW EO SUPPORT  W_{prop} = 5,000 LB	• SINGLE STAGE • $\frac{W_{pay}}{W_{prop}} = 7.1$				

Figure 18. Off-Loaded Performance

of a 10,000 pound (4540 kg) payload to geosynchronous orbit, and for a round trip 20,000 pound (9100 kg) payload lunar landing mission. The capability is shown in terms of an efficiency coefficient (ratio of payload/propellant weights). Planetary capabilities are shown on the basis of maximum payload injected out of earth orbit.

A comparison of the space tug concepts for the small characteristic velocity, low earth-orbit support missions indicates that large space tugs with large crew modules compare favorably with the small, optimized space tug for this mission. All of the concepts have been off-loaded for a single mission for this comparison. When off-loaded to accomplish the geosynchronous mission in a two-stage recoverable mode, the lunar landing concept is comparable to the optimized two-stage geosynchronous concept, and the two stage concepts have about 8 percent better performance than the optimized single stage concept. Off-loading of the large geosynchronous mission vehicle to accomplish the lunar landing mission requires about 10 percent more propellant than the optimized lunar landing space tug. Use of the space tugs in a two stage mode to accomplish the planetary missions results in very large payloads which are greater than those currently planned for the forseeable future. The 80,000 pound (36,200 kg) propellant capacity stage is the only one of these that can accomplish the near planetary missions in a single stage recoverable mode. In this mode, it has the capability of injecting 13,000 pounds (5900 kg) of payload.

These results indicate that, from a performance point of view, multi-purpose use of space tug concepts to accomplish a wide variety of missions does not lead to serious performance penalties.

Crew Module Matrix

Figure 19 shows the types of crew modules and position of the crew module on the propulsion module. A vertical cylinder was considered because of the relative ease of integrating it with cylindrical propulsion modules. The horizontal cylinder was considered because of its potentially superior functional characteristics when used as a lunar surface shelter. Diameters ranging from 12 feet (3.7 m) to 22 feet (6.7 m) were considered for the vertical cylinder.

Both top and bottom mounting of the crew modules were considered to satisfy mission-peculiar functional requirements. Top mounting of the crew module is desirable for earth-orbital mission functions; whereas, bottom mounting appeared desirable for the lunar landing missions to improve ingress and egress, lower the center of gravity, improve landing visibility, and to avoid excessive propulsion module loading when landing.

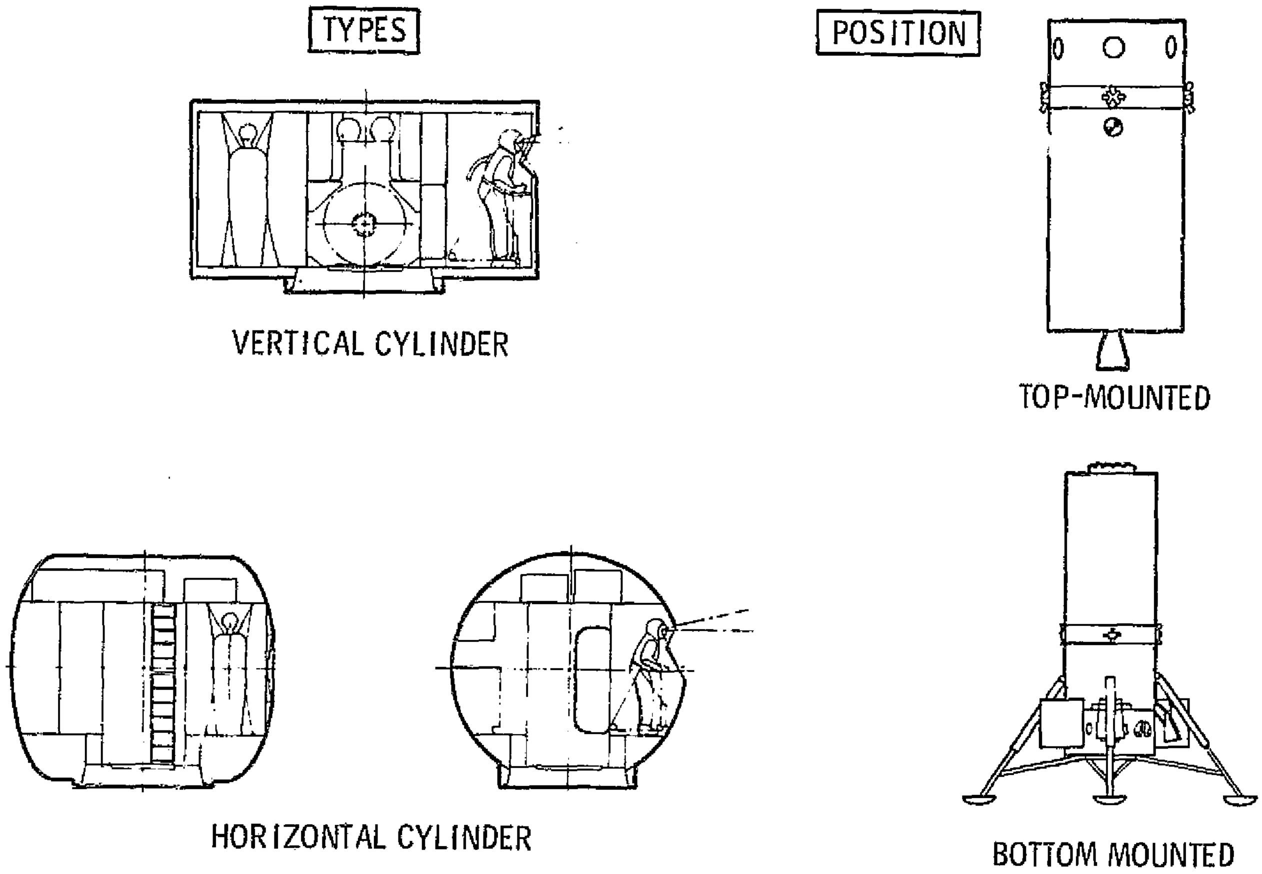


Figure 19. Crew Module Concepts Matrix

Intelligence Module Matrix

The three basic concepts considered for the intelligence module are shown in Figure 20 and vary from totally modularized to partially modularized to totally integrated within the propulsion module. Several key studies were conducted to obtain data comparing these concepts. Consideration was given to the potential uses of a totally modularized intelligence module (IM) as a free flying unit, without the propulsion module. Additionally, consideration was given to use of the IM with other IPP elements either partially or in total. Other considerations include a comparison of performance penalties because of modularization and the relative ease of fabrication, checkout, and replacement of components. The totally modular concept was retained as a baseline during the study.

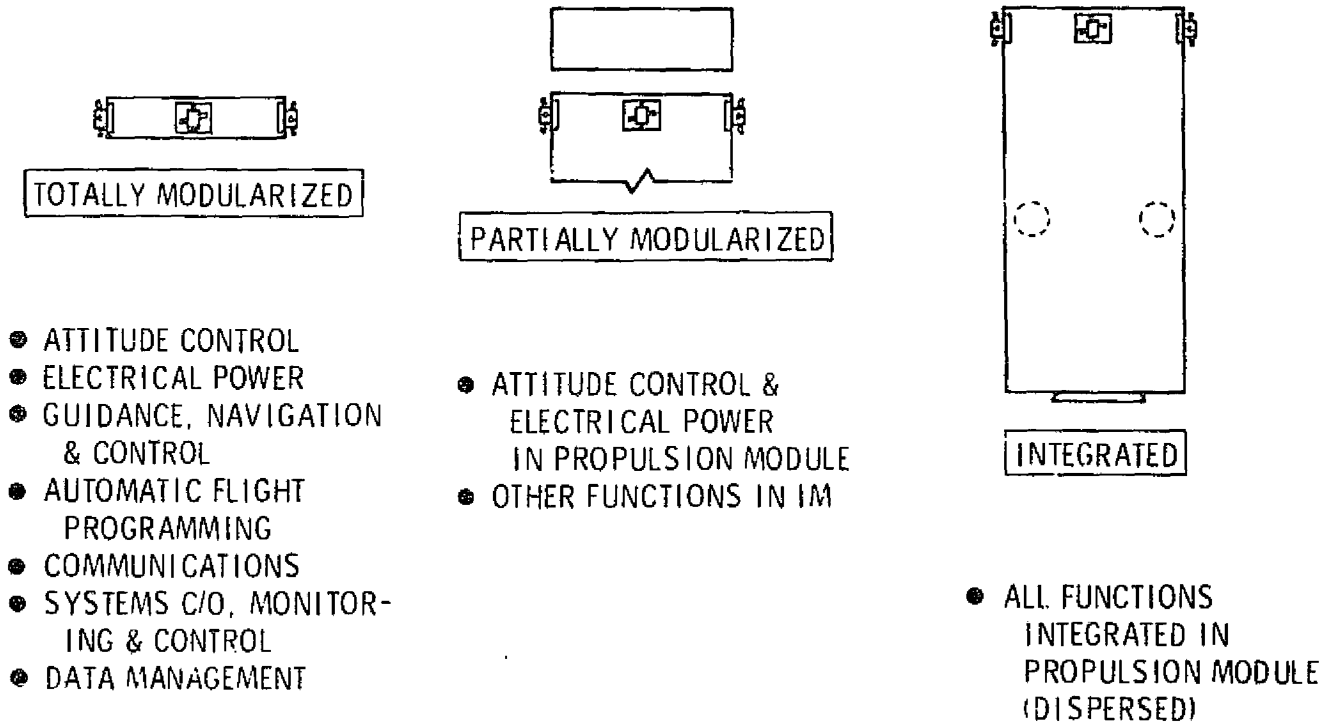


Figure 20. Intelligence Module Concepts Matrix

BASIC SYSTEM REQUIREMENTS

This section presents the basic system requirements for each of the major modules (propulsion, intelligence, and crew) and describes the overall interfaces between the modules. Problems related to concept modular arrangements for space and lunar landing missions are also discussed.

Propulsion Module Design Constraints

The primary factors affecting the design of the propulsion module are shown in Figure 21. Since transport of the tug to and from orbit is provided by the EOS, the diameter must be less than the EOS cargo bay diameter constraint for payloads, which is currently 15 ft (4.6 m). The length of the propulsion module plus other modules or payloads attached to it during transport should be less than the EOS bay clear length to avoid space assembly. This dimension is 60 feet (18.3 m) in the current EOS design.

An aft docking port may be necessary to (1) allow handling of two payloads simultaneously during payload transfer missions (the other payload is attached at the front of the PM to a docking port attached to the intelligence module), (2) allow attachment of a second PM for two-stage missions,

(3) allow possible aft attachment of the crew module if it is desirable for lunar landing missions, and (4) allow docking with the EOS. Other operational approaches are being considered that may eliminate the need for a rear docking port and multiple engines. This would lead to a much simpler design than the one shown in Figure 21. This concept is, however, being retained as a baseline and results of design variations are presented in the Phase II discussion.

The propellant capacity of the propulsion module may be between 8,000 and 80,000 pounds (3600 to 36,000 kg) dependent upon concept. Total maximum thrust of the main engines is about 35,000 to 40,000 pounds (155,000 to 178,000 N), with a throttling ratio between 7:1 and 10:1. Maximum thrust results from performance optimization for the geosynchronous mission and the throttling ratio results from the requirement to land on the lunar surface.

Figure 22 shows a profile of concept 11 which is comprised of a small stage with 9000 pounds (4100 kg) propellant capacity and a tank set which may be expended on some missions with 48,000 pounds (21,800 kg) of propellant. This concept is considerably different from the others because of the different tankage sizes. The primary reason for consideration of this concept was to minimize the amount of propellant required for the geosynchronous mission while also minimizing the cost of expenditure.

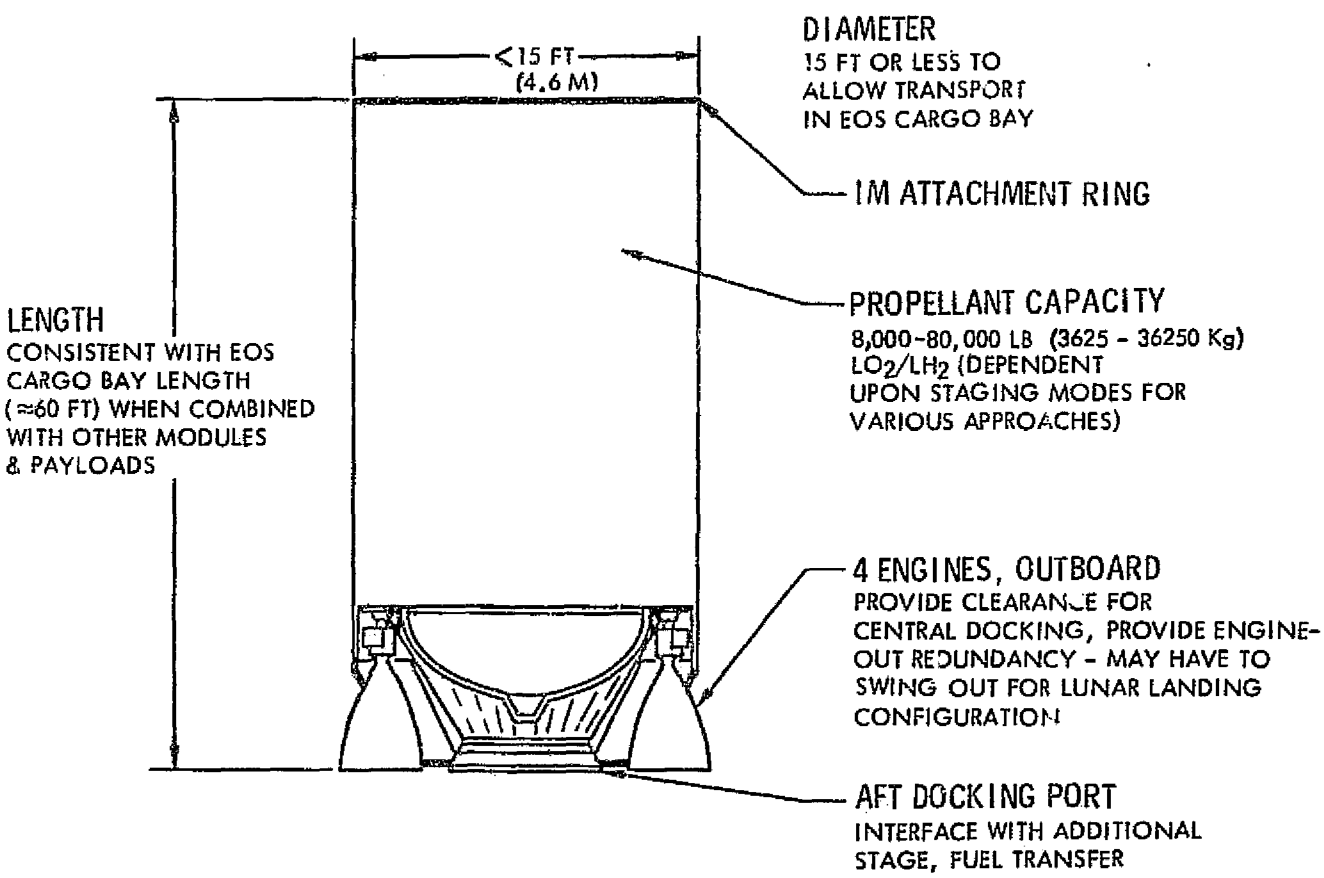


Figure 21. Propulsion Module Design Constraints

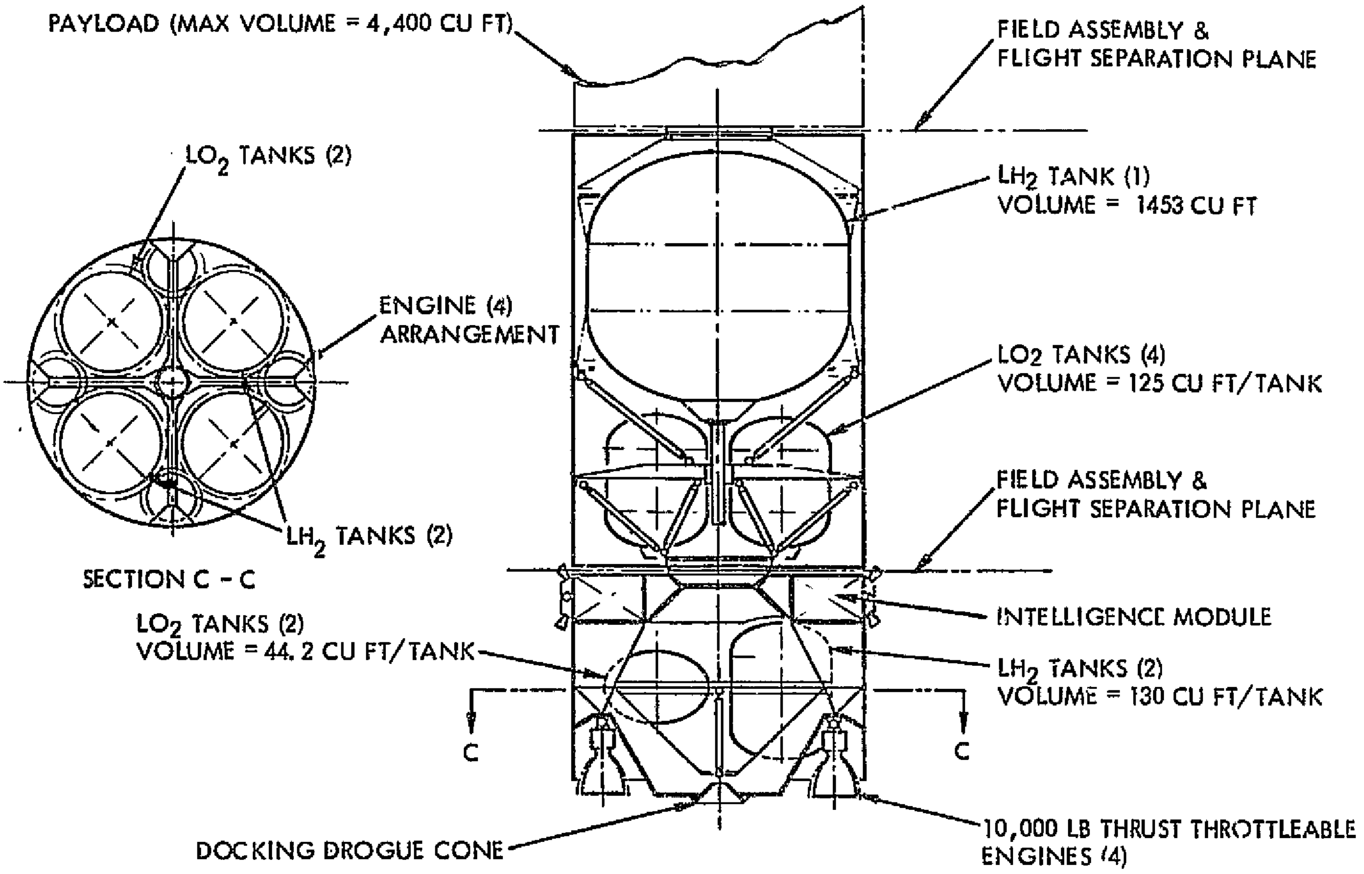


Figure 22. Stage and One-Half Configuration

Since the intelligence module is the most expensive portion of the space tug, the small stage was designed to return it from geosynchronous altitude to low earth orbit for reuse. The tank set is designed to be expended when the payload is injected at geosynchronous altitude.

In analyzing this configuration, it was found to have some very interesting features. First, it is compact compared to other concepts and can readily fit into the EOS with payloads for the geosynchronous mission. Second, it has a propellant loading nearly the same as the optimized lunar landing vehicle and, therefore is efficient in accomplishing the lunar mission. Third, the small stage can be used alone to efficiently accomplish the low ΔV, low earth-orbit support missions as a space based stage. Finally, the small stage can be placed in the EOS with large payloads, if desired, and be used for low ΔV missions in conjunction with the EOS as a third stage for payload transfer missions and for some of the sun-synchronous and other moderate ΔV missions beyond EOS capability.

The influence of space tug engine and pressurization systems are shown on Figure 23 for single-stage and two equal-size stage systems for 90,000 pounds (41,000 kg) of propellant. The 90,000-pound (41,000-kg) propellant loading was selected to allow a positive value of payload for concept

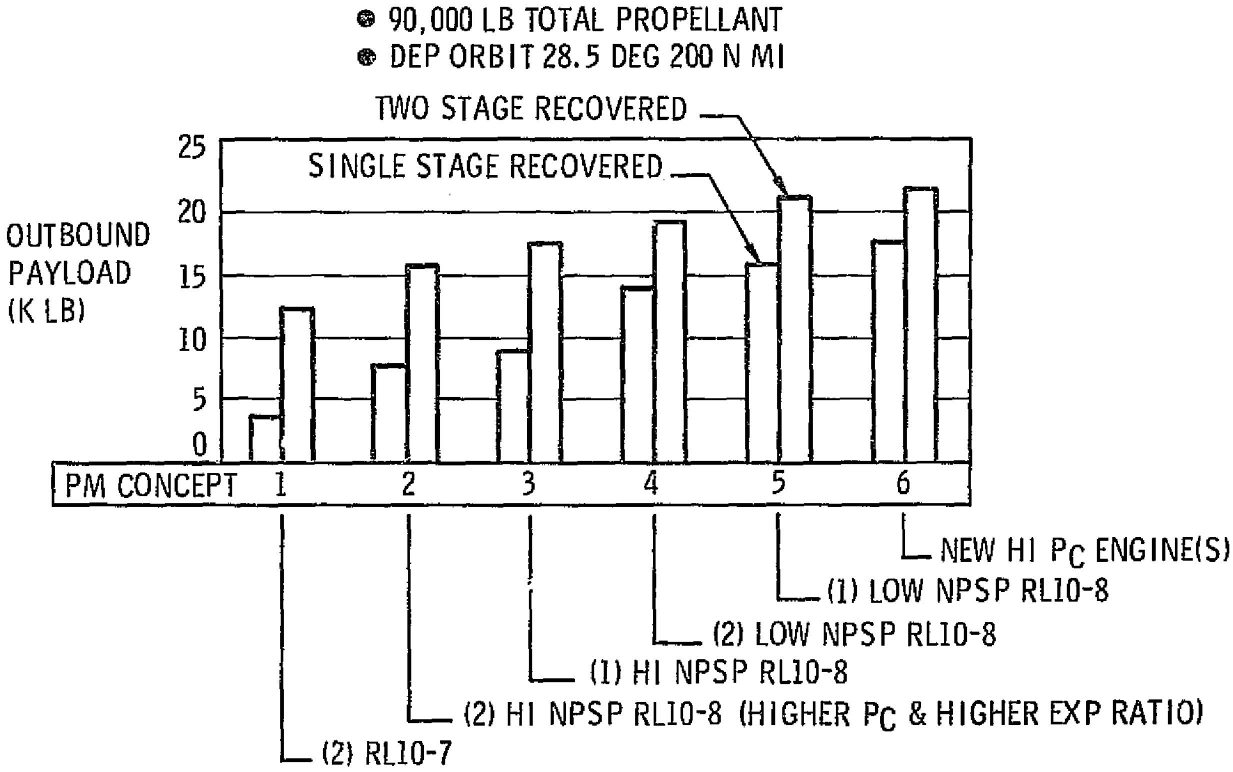


Figure 23. Geosynchronous Mission Propulsion Concept Comparison

number 1 (RL 10-7 engine). These data, which are for the geosynchronous mission, illustrate the effect on payload weight of engine type, number of engines and NPSP (net pump suction pressure). The existing RL10-7 is compared to an improved version, the RL10-8, for uprated thrust [from 15,000 to 23,400 pounds (67,500 to 105,000 N)] and increased I_{SP} and for the additional improvement in the pump to allow low NPSP operation. Performance of a new high chamber pressure engine is also shown for comparison.

These data show that a single RL10-8 engine provides better performance than two RL10-8 engines despite the higher thrust/weight of two engines. Furthermore, large performance gains are realized by the increased I_{SP} of the RL10-8 and even greater gains are realized by going to a new pump that provides low NPSP. A combination of these improvements leads to performance which is only slightly less than that obtained by a new high chamber pressure engine. The required changes to the RL-10 to achieve this level of performance appear to be rather drastic, involving a new pump, an increased engine chamber pressure, a new extended nozzle to obtain large expansion ratios and higher I_{SP}, and throttling over a range of about 10 to 1 to satisfy all space tug mission thrust requirements.

Similar data are shown in Figure 24 for the lunar landing mission where payload is carried to the surface only and the tug is recovered in lunar orbit. This chart indicates an improvement from 56,000 pounds (25,400 kg) of payload to 65,000 pounds (29,500 kg) of payload across the range of variables previously described. Although the payload increase is not as dramatic for the lunar mission as it is for the geosynchronous mission, the requirement to resupply the space tug propellants from the earth's surface to lunar orbit for this mission magnifies the apparent efficiency gains as compared to the geosynchronous mission [about 2.2 pounds or 1.0 kg of propellant are required for delivery from earth orbit of a pound (0.45 kg) of payload to lunar orbit].

Crew Module Design Constraints

Figure 25 shows the two crew modules being considered for multi-purpose space tug applications and the major factors that constrain their design. Because of the long stay time on the lunar surface for 4 men (28 days), the free volume allotment and the relative functional layout of the crew module in this application are primary drivers to the volumetric and area requirements. Another important constraint, however, is the dimensional clearances when the crew module is brought up in the EOS. The desire to integrate the crew module to the other modules on the ground also leads to important dimensional constraints which influence the total volume available for the horizontal cylinder more seriously than for the vertical cylinder.

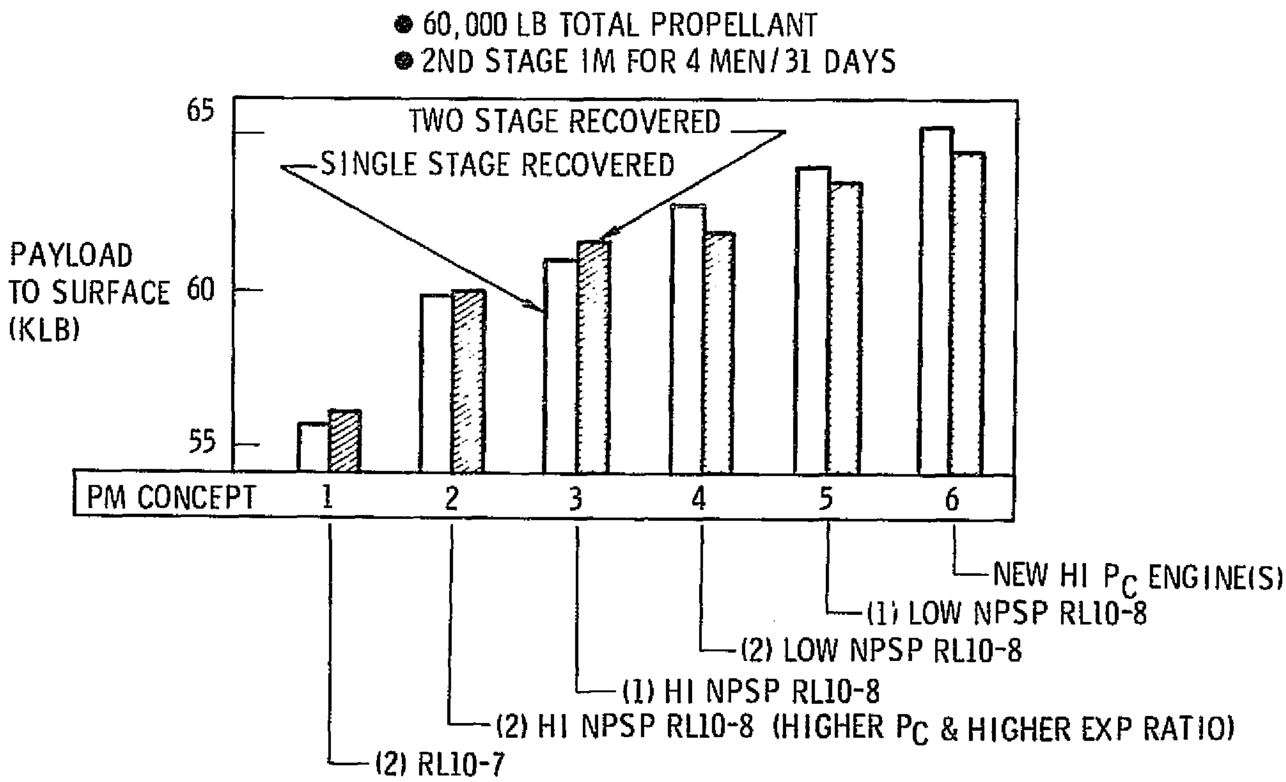
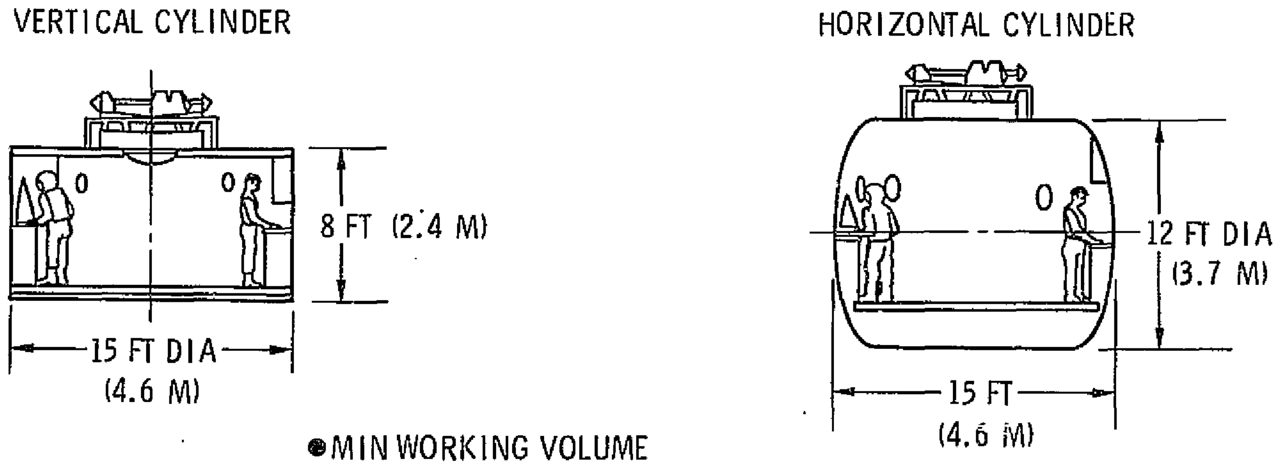


Figure 24. Lunar Landing Mission Propulsion Concept Comparison



- MIN WORKING VOLUME
- EOS DIMENSIONAL CLEARANCE
- INGRESS-EGRESS PROVISIONS
- STRUCTURAL INTEGRATION WITH VEHICLE
- DESIGN MISSION CAPABILITY
  - 1 OR 2 MAN CONTROL
  - 6 MEN TO 7 DAYS
  - 4 MEN 28 DAYS LUNAR STAY
  - 12 MAN RESCUE

Figure 25. Crew Module Design Constraints

Provisions must also be made for crew ingress and egress when attached to another IPP element such as a space station and for lunar surface access. To avoid dumping all of the air in the crew module and to allow functioning of other crew members in shirt sleeves, an airlock must be provided, particularly for the lunar landing mission when numerous egress and ingress operations occur. A second hatch also must be provided to assure safe ingress or egress should a failure occur in the airlock.

Attachment of the landing gear to the crew module for the lunar landing mission, docking loads with other IPP elements, and impingement of the main engine or attitude control engine exhaust plumes on the crew module are examples of loading conditions that may seriously impact the crew module structural approach.

Because of the large variety of missions that the crew module must accomplish, including those shown in Figure 25, it is not possible to provide a single internal crew module arrangement that is satisfactory for all missions. It is anticipated that the external shell will be common to all missions, but internal arrangements will be a special function of mission.

Intelligence Module Design Constraints

The intelligence module, shown in Figure 26, contains all of the components necessary to conduct unmanned missions when combined with the propulsion module or to conduct manned missions when combined with the propulsion module and crew module. This module is the control center of the space tug concept and as such it must provide (1) the capability for control of the main propulsion system thrust level and thrust vector orientation; (2) rotational and translational control for precision maneuvering (e.g., docking); (3) programming of all flight functions; (4) guidance and navigation; (5) power for manned and unmanned missions; (6) systems checkout, monitoring and control; (7) communications; (8) data management; and (9) crew module interface for power, data displays, and command and control override.

Because of the EOS cargo bay diameter restriction, its diameter cannot exceed 15 feet (5.2 m). This poses particular problems for the attitude control thrusters which must extend beyond the propulsion module for control. The design illustrated in Figure 26 shows two solutions: a rotating door or a hinged door to allow extension of the ACS when on orbit. The attitude control thrusters shown in this design utilize gaseous H_2 and

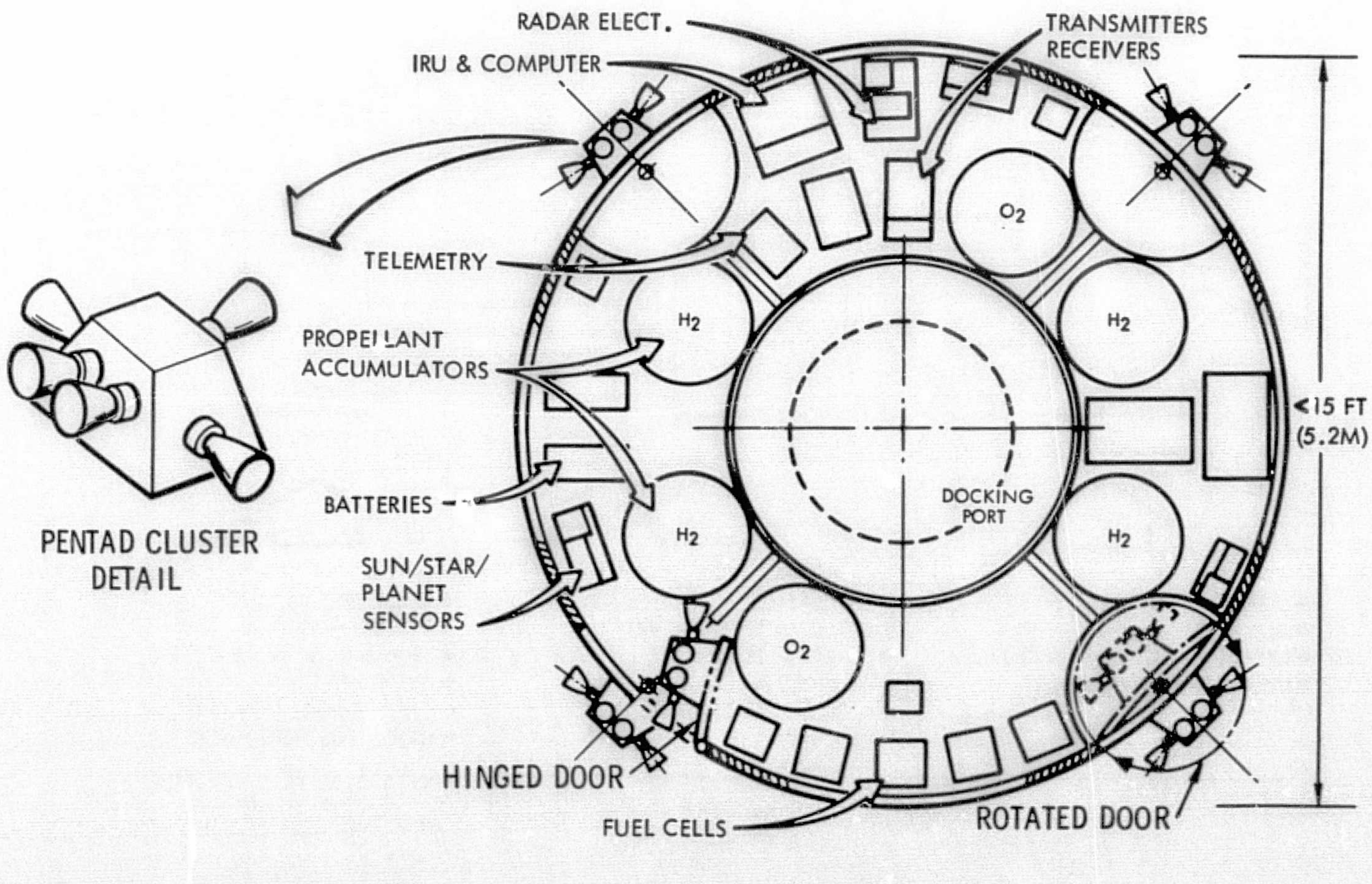


Figure 26. Intelligence Module Design Constraints

O_2 in a pulsed mode for control impulse. They are sized for approximately 200 pounds (890 N) maximum thrust and are fed from the propulsion module tanks. A pump and heat exchanger system located in the propulsion module converts the liquid to gas and pumps the gases at high pressure into gas accumulators located in the IM.

If the IM is attached to the forward end of the propulsion module, it must have provisions for a docking port to dock with the crew module, payloads, and other integrated program plan systems.

System Interfaces

Figure 27 summarizes the functions and interface characteristics assumed for the baseline space-tug system. As indicated, several interfaces exist between the propulsion module and intelligence module and between the intelligence module and the crew module. Although many of these interfaces are electrical, some are gas or fluid interfaces. The gas and fluid interfaces exist because of the desire to use common tankage from the propulsion module for the attitude control system, for fuel cell power, and for crew water and oxygen.

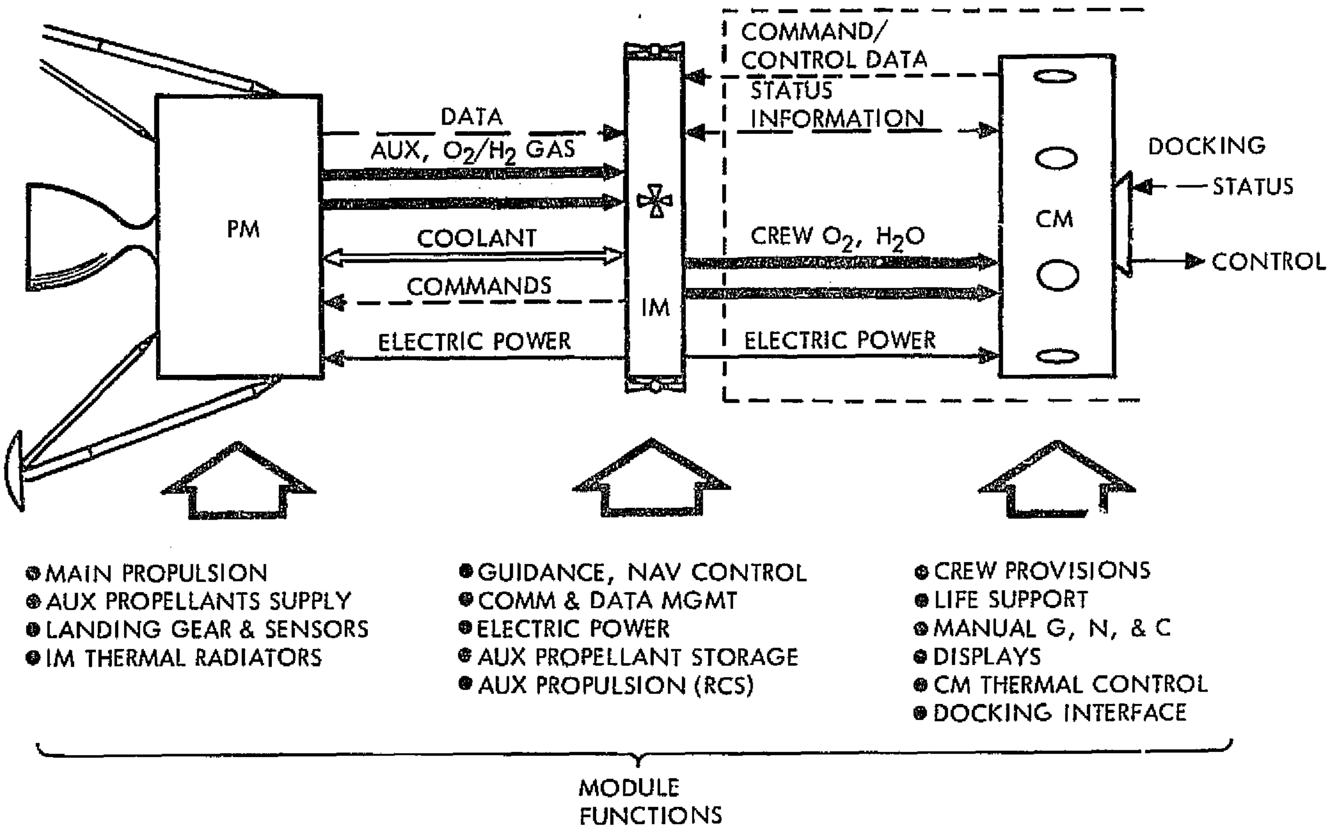


Figure 27. Module Functions and Interfaces

Integration of the space tug modules to obtain multipurpose capability leads to potentially serious compromises, particularly when the requirements for a lunar landing mission are compared with missions requiring only space operations. These compromises are illustrated on Figure 28.

For the lunar landing mission, it is desirable to have the crew module and the cargo modules near the surface. A low crew module provides better visibility on landing and much improved crew ingress and egress to and from the surface as compared to a top-mounted crew module [the crew module would be about 55 feet (16. 8 m) from the surface if mounted on top of the propulsion module]. The cargo modules should also be located near the surface to allow easy access to the cargo. Two other important reasons exist for low locations of the crew and cargo modules: (1) a low location reduces the center-of-gravity and results in a smaller landing gear spread, and (2) top-mounting of the crew and cargo modules result in a 20,000-pound (9100 kg) load (under 1 earth-g condition) on top of the propulsion module which, under several g's landing load (3 to 6 g), leads to large design structural loadings on the propulsion module.

During launch in the earth orbital shuttle, the longitudinal acceleration reaches approximately 4 g. This implies that a tug fully loaded with propellant would have larger reaction forces in the EOS due to hydrogen and oxygen tank support than for lunar landing (where the tanks are only 1/3 full). Assuming that the space tug is appropriately supported in the EOS,

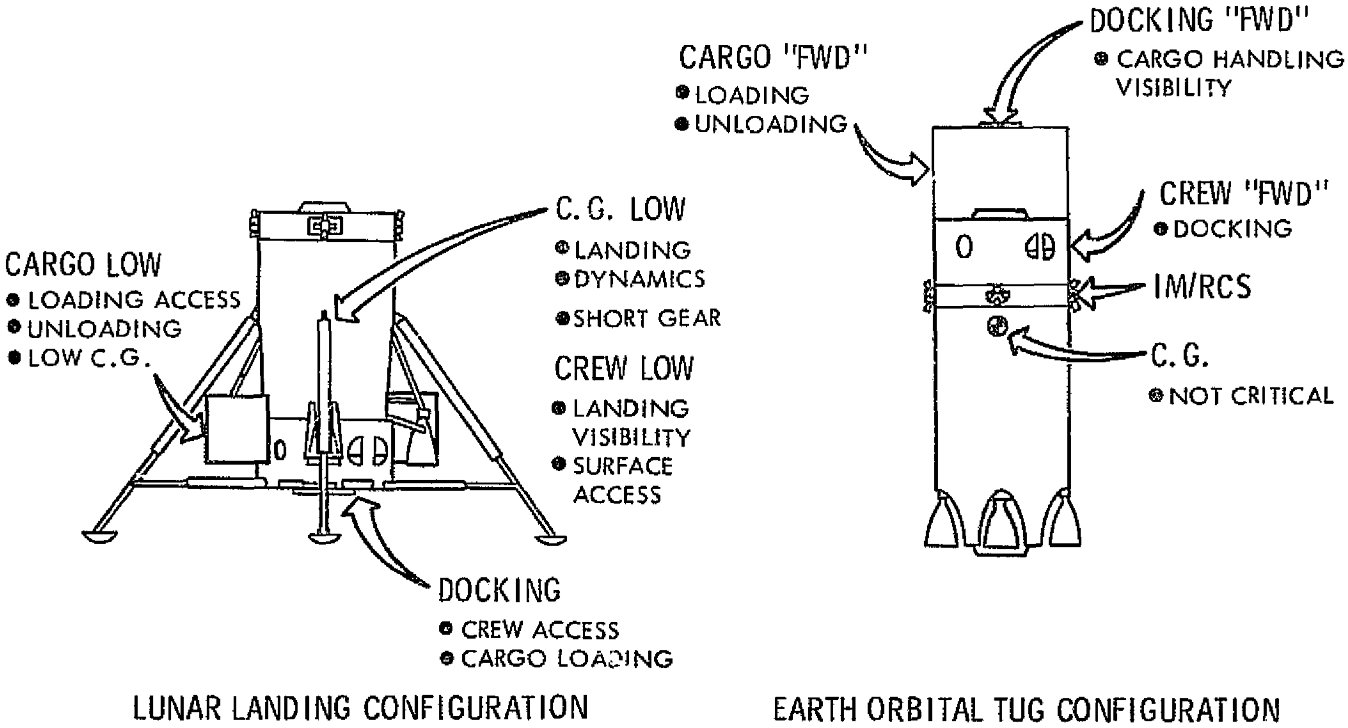


Figure 28. Tug Module Locations

loadings of the propulsion module structure caused by payloads can be reacted into the EOS bay structure. For this reason, a top-mounted crew module would produce greater loads for landing on the lunar surface than those experienced by the tug from top mounted payloads in the EOS environment.

For space missions, the center of gravity location is not critical, and a high location of the crew module is desirable for normal forward-oriented docking operations with payloads and other integrated program plan systems. Such design compromises require considerable analysis to determine the detailed implications of providing multipurpose functions.

The approach being considered for alleviation of the penalties on the propulsion module related to the lunar landing mission are illustrated in Figure 29. First, it should be noted that the propulsion module is approximately 1/3 full upon landing on the lunar surface. This helps to reduce the loads within the propulsion module from the propellant tanks. Loads introduced by the cargo module can be eliminated if they are picked up either through the crew module or the landing gear kit or both. Crew module loads into the propulsion module can be eliminated by placing the crew module on the bottom of the propulsion module. Finally, reaction loads introduced by the landing gear can be minimized by picking up the loads on the crew module as much as possible and increasing the gear stroke, thereby reducing landing g. Additionally, experience gained from the Apollo lunar landings and improvements in landing approach systems

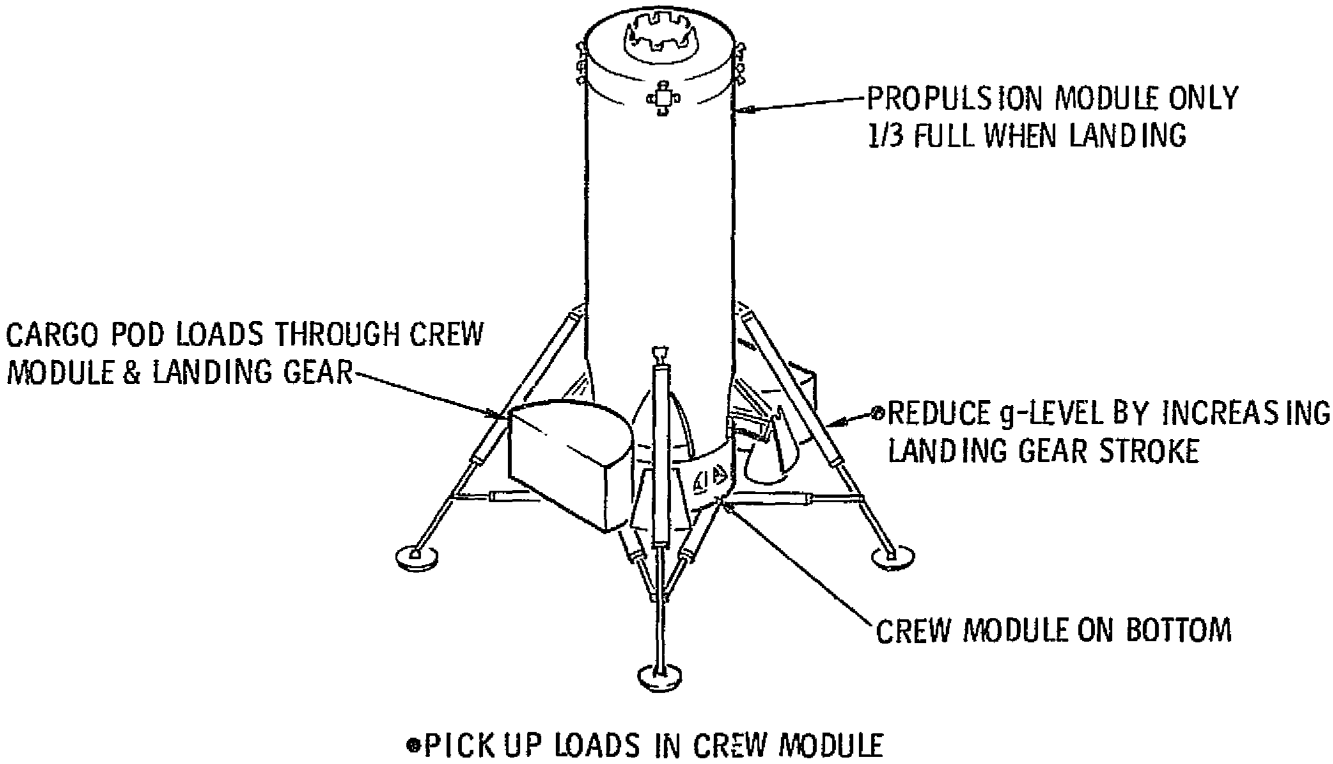


Figure 29. Alleviation of Lunar Landing Penalties on Propulsion Module

may allow a significant reduction in landing velocity, thus reducing landing gear stroke requirements for a given g level.

Because of the interfaces among modules previously described, it is highly desirable to maximize the degree of integration of the modules on the ground to allow simple operations and to allow integrated ground checkout of all systems prior to launching in the EOS. This appears to be particularly important for the crew and intelligence modules which may have complex interfaces.

Because of the restricted size of the EOS and the potentially large size of some of the space tug approaches when integrated, the ability to accomplish ground integration is highly sensitive to EOS bay size changes and space tug trade studies. EOS payload weight restrictions can also influence the degree of integration should EOS payload capability fall into the region of less than 20,000 pounds (9100 kg). Under any circumstances, it appears that space integration of some of the modules, such as cargo pods and landing gear will be necessary for the lunar missions. These, however, are mechanical connections, and do not pose the problems related to the crew, intelligence, and propulsion modules. Payloads will also have to be integrated routinely on orbit, but this is not considered to be a difficult operation in comparison to other potentially required operations. Standard docking gear will probably be used to allow such operations. As the space tug program progresses, it is anticipated that the ability to mate modules on orbit (including mechanical, electrical, and fluid interfaces) will become a routine operation. Considerable experience will be required to achieve such proficiency.

CONCEPTS EVALUATION

During the later part of the Phase I studies, an evaluation was conducted to select up to three concepts for more detailed studies during the second phase of the contract. Primary emphasis in this evaluation was placed on the propulsion module concepts shown in Figure 17, further analysis being required to evaluate the crew and intelligence module approaches. Several key studies conducted during the first phase in the mission and operations area and the concepts design and subsystems areas contributed to this evaluation.

Figure 30 shows the primary and secondary factors considered in evaluating the various propulsion module concepts. Four main categories were considered: economics, growth potential and versatility, operations complexity, and risk.

Total program cost was considered in comparing the various concepts, and both the baseline program model and several variations to this model were considered. Growth potential and versatility evaluation considered the ability of the concepts to conduct missions of greater difficulty within the classes of missions already considered for the tug as well as the ability to conduct missions beyond those currently defined.

CONCEPT	ECONOMICS		GROWTH POTENTIAL & VERSATILITY		OPERATIONS COMPLEXITY			RISK
	BASELINE PROGRAM	SENSITIVITY	WITHIN MISSION CAPABILITY	ALTERNATE MISSION CAP.	MISSION SUCCESS	SPACE OP'N COMPLEXITY	INTEGRAL EOS LAUNCH	WEIGHT GROWTH SENSITIVITY
1								
2								
3								

Figure 30. Evaluation Factors

Operations complexity evaluation considered mission success, the complexity of space operations, and the ability to launch the concepts into earth orbit. The final category, risk, was based on the sensitivity of concept to growth in system inert weight. Technology risks were not considered pertinent since all concepts utilize similar technology. Further, the technologies characterized by EOS and the space station appear to provide a sufficient base for the development of the space tug.

Economic Evaluation

The approach to building up the cost data is shown on Figure 31. The costs considered are comprised of the cost of the hardware (including development cost as well as unit cost), the costs related to delivery of the space tugs to low earth orbit or lunar orbit and the cost of delivering propellants for use in the tug to low earth orbit and lunar orbit. Although payload costs comprise a major part of total program cost, they were not considered as a part of an analysis aimed at comparing space tug concepts. Costs of delivering the tug payloads to earth or lunar orbit are not included in the buildup.

A computer program was used to process the input data which consisted of parametric tug cost data, data on the number of reuses, EOS and translunar shuttle delivery costs, and a mission model which included

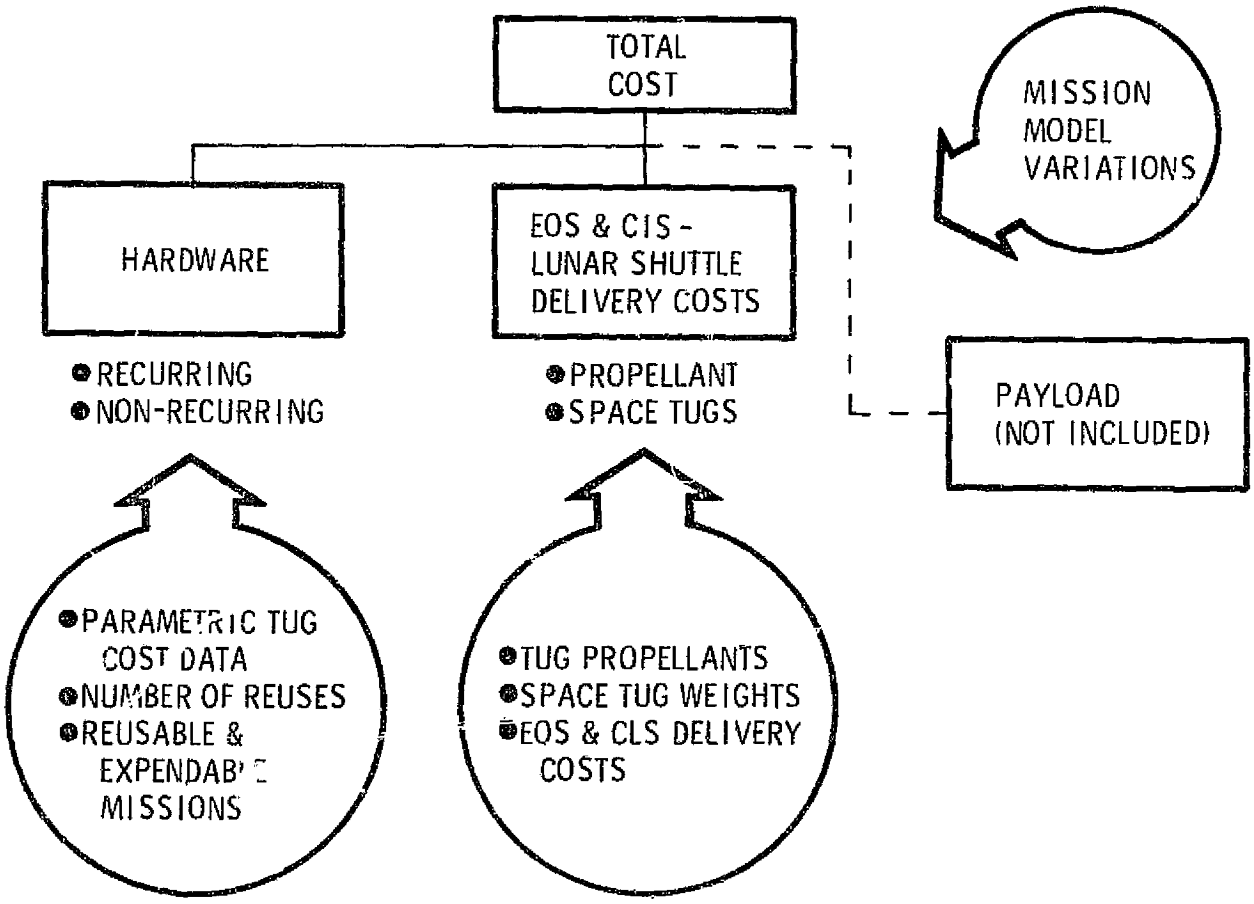


Figure 31. Cost Data Buildup

payload data, mission segment data, and space tug propellant requirement data for each mission. These data were processed within the computer to determine when a tug had been used for the maximum number of missions and whether a tug was available for a mission requiring expenditure or if a unused or partially used tug would be used for a mission requiring expenditure. The cost data were output for each concept and for each mission on a yearly basis and total basis.

Table 1 summarizes the major assumptions used in developing the baseline cost data, including space tug recurring cost, number of reuses, and EOS and cislunar shuttle transportation systems.

Figure 32 compares the total program cost for the concepts under consideration, including the breakdown in cost related to each program area. This data indicates that only concepts 6 and 7 show relatively large increases in program cost compared to the other concepts. Their large program costs are caused by the necessity to expend all or part of the tug on the geosynchronous and planetary missions. Concept 6 is lower in cost than concept 7, because only a stage without an intelligence module is expended for the geosynchronous and near planetary missions. Concept 7 expends a stage and an intelligence module for these missions. Concept 8 was eliminated prior to the economic evaluation, because it requires the expenditure of a stage and intelligence module for the high delta-V missions while still

Table 1. Baseline Cost Model Summary

- SPACE TUG FIRST UNIT RECURRING COST = f (PM: SIZE AND MODULES USED)

  PM \$8.9M(11), 11.3M(5), & 13.2M(1)
  IM \$38.3M
  CREW M \$18.8M
  LANDING GEAR \$2.2M
  TANK SET (11) \$6.7M
- NUMBER OF REUSES

  PM - 10 FOR HIGH ΔV MISSIONS
  PM - 50 FOR LOW ΔV MISSIONS
  IM - 10 FOR HIGH ΔV MISSIONS
  IM - 50 FOR LOW ΔV MISSIONS
  CREW M - 3 YEAR LIFE
  LANDING GEAR - 10 LUNAR LANDINGS

- EOS AND CIS-LUNAR SHUTTLE TRANSPORTATION SYSTEMS

  EOS PAYLOAD - 45,000 LB TO 31° AND 100 N MI, 25,000 LB TO 55° AND 270 N MI
  EOS COST - \$4.5 $\overline{M}$/FLIGHT
  CLS PAYLOAD 130,000 LB OUT WITH 20,000 LB RETURN
  CLS COST - \$66.0 $\overline{M}$/FLIGHT

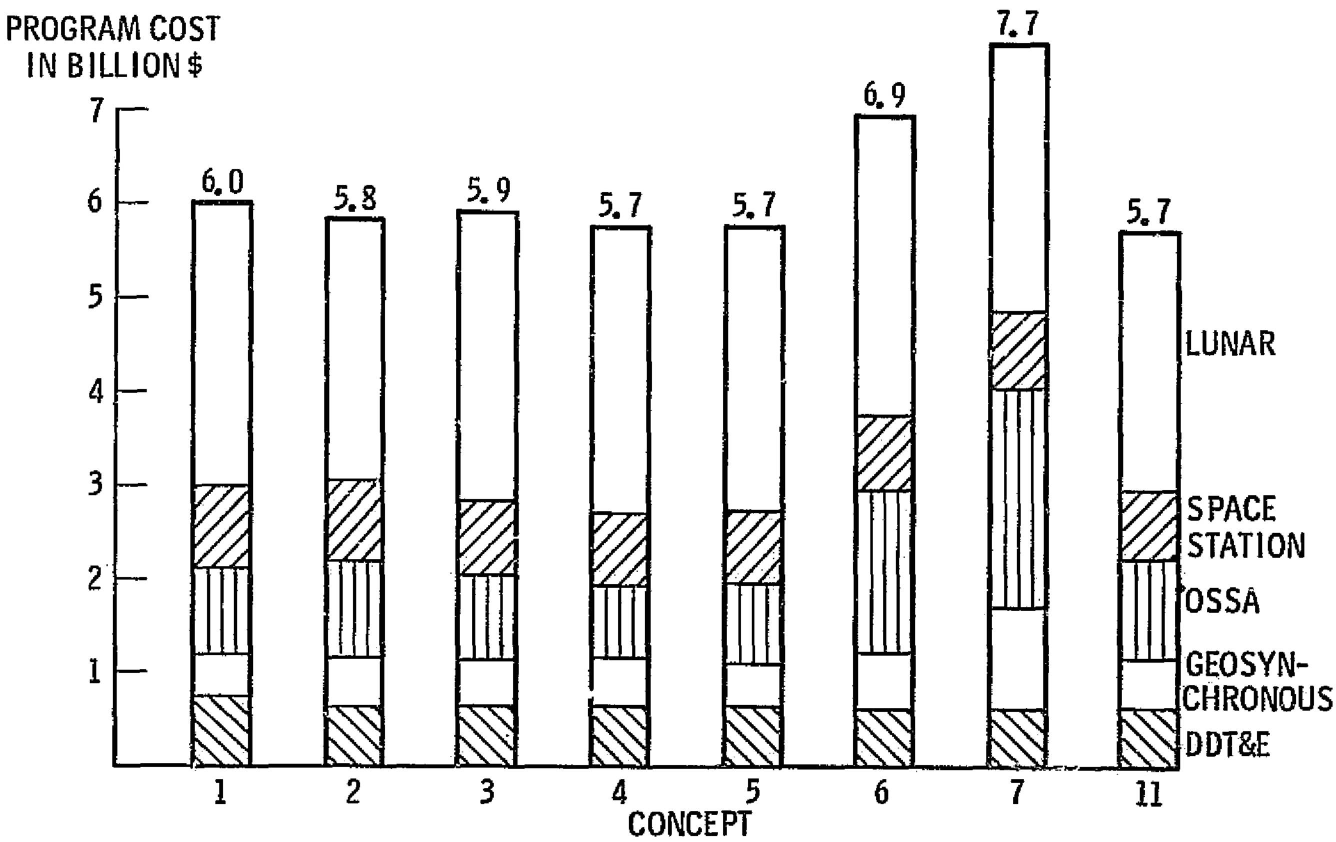


Figure 32. Space Tug 10-Year Total Program Costs

requiring a complex two-stage mission mode. As previously explained, concepts 8 and 10 were eliminated early in the study, because they could not accomplish all of the missions.

All other concepts are comparable in total program cost. Concept 11, which expends a tank set for the geosynchronous and near planetary missions, shows a program cost comparable with the fully recoverable versions. The recurring cost of the tank set and the propellants saved tradeoff favorably. The small stage [8800 pounds (4000 kg)] also reduces somewhat the costs of conducting the low delta-V missions.

To determine whether the program costs for the concepts are sensitive to the baseline assumptions, sensitivity data were obtained. The number of propulsion module reuses were varied between 10 and 30 for the high delta-V missions and between 50 and 150 for the low delta-V missions. Traffic model variations included: (1) a low, stretched-out program, (2) a high program, which had a 50-percent increase in OSSA mission traffic (including geosynchronous), and (3) independent assessments of cost in each mission category. Additionally, EOS and cislunar shuttle delivery costs were varied by ± 33 percent. The low traffic model assumed the same OSSA (including geosynchronous) traffic as that of the baseline, but the IOC dates of the various IPP systems were stretched out (Earth Orbital Shuttle 1980; Space Station assumed 12-man in 1981, 50-man in 1987, and 100-man in 1991; and the lunar program was initiated in 1983). For this reason, it was assumed that the unmanned earth orbital tug was introduced in 1981, the manned earth orbital tug in 1983, and the lunar landing tug in 1983.

Table 2 presents the data for the baseline traffic model and for the variations to the baseline plan. The cost sensitivity data include only the recurring cost and should be compared with the recurring baseline cost data. A comparison of costs in each category for the various concepts indicates that no significant difference in cost exists for concepts 1, 2, 3, 5, and 11.

A comparison of concepts within the geosynchronous mission class only indicates that the recoverable single-stage tug (concept 1) has the lowest program cost; however, the difference between the single-stage and the two-stage recoverable tug (concept 5) is only 15 percent. The cost for the two-stage tug is higher because of the increased recurring space tug cost related to the use of two stages to accomplish the mission. This cost increase is greater than the saving in propellant delivery costs for the two-stage system. A comparison of the concepts within the space-station-only category (which are all low delta-V missions) shows that the cost decreases with space tug size. All of the concepts have been off-loaded for accomplishing missions in this category, because they are considerably oversized for accomplishing these missions. When compared to a space tug optimized to accomplish these missions and which has a space-station-only recurring

Table 2. Baseline Traffic Model Data

CONCEPT	BASELINE COST: NON-REC.	BASELINE COST: REC.	BASELINE COST: TOTAL	COST SENSITIVITY: TRAFFIC MODEL	NO. OF REUSES	MANNED VS. AUTOMATIC	LUNAR & L.E.O. DELIVERY COST	LUNAR MISSION MODEL	OSSA ONLY	GEO-SYNCH ONLY	SPACE STATION ONLY	LUNAR ONLY	OSSA & GEO-SYNCH. ONLY
1	0.66	5.37	6.04	HIGH 5.96 / 5.01 LOW	4.06 / 4.58	AUTO 5.24	HIGH 6.40 / 4.35 LOW	HIGH 6.76 / 4.07 LOW	0.93	0.45	0.87	3.09	1.38
2	0.67	5.21	5.83	5.86 / 4.88	3.97 / 4.28	5.08	6.21 / 4.40	6.46 / 4.03	1.03	0.53	0.81	2.81	1.56
3	0.61	5.26	5.87	5.87 / 4.91	4.04 / 4.34	5.13	6.30 / 4.23	6.61 / 4.01	0.94	0.50	0.80	3.00	1.44
5	0.60	5.07	5.67	5.64 / 4.73	3.82 / 4.13	4.94	6.03 / 4.11	6.38 / 3.84	0.89	0.52	0.78	2.94	1.32
~~6~~	0.59	6.29	6.88										
~~7~~	0.59	7.14	7.72										
11	0.61	5.09	5.70	5.79 / 4.78	4.03 / 4.30	4.96	5.96 / 4.22	6.30 / 3.97	1.10	0.53	0.72	2.73	1.63
COMMENTS	CONCEPTS 6 & 7 ELIMINATED BY HIGH COST			← NO SIGNIFICANT DIFFERENCE →					NOT SIG.	NOT SIG.	SIMILAR TO OPT. COST OF 0.74 M	NOT SIG.	NOT SIG.

*FOR CERTAIN EARTH ORBITAL MISSIONS, IT WAS CONSIDERED THAT MANNED OR UNMANNED (AUTOMATIC) MISSIONS WERE OPTIONAL. THESE INCLUDE PAYLOAD TRANSFER AND NEAR SPACE-STATION EXPERIMENT MODULE MISSIONS. THE BASELINE ASSUMES THAT THESE ARE MANNED MISSIONS.

cost of $0.74B, concept 1 has about a 17-percent cost increase. This indicates that off-loading of large stages to accomplish these missions does not lead to highly inefficient operations. Concept 11, because of the small stage size without the tank set, has excellent performance in this category. Concept 11 also compares favorably with concept 2 (the optimized mode A lunar landing vehicle) in the lunar mission area, because the total propellant loading in the tank set and the small stage is near optimum for this mission mode. As shown, off-loading the largely oversized concept 1 for this mission does not significantly increase the lunar program cost (about 6 percent).

Based on these data, concepts 6 and 7 were eliminated from further consideration, and all other concepts were considered to be comparable economically. For this reason, several options still existed following the economic evaluation and the selection of concepts requires considerations in the other categories.

Growth Potential and Versatility

Two evaluation categories were considered in evaluating growth potential and versatility: (1) the ability of the concepts to conduct more difficult missions within the mission areas considered as primary for the

tug (payload within mission categories) and (2) the space tug ability to perform missions that have not been considered prime space tug missions (alternate mission capability). Evaluation in these categories is described in the following paragraphs.

Table 3 lists the maximum payload capability of the concepts surviving the economic evaluation in the mission categories currently being considered for the space tug. The low earth orbit, small delta-V area is not significant, because all of the concepts are oversized for these missions. In the geosynchronous mission area, concept 1 has considerable growth potential as a two-stage configuration and can emplace up to 48,000 pounds (21,800 kg) of payload. Concepts 1, 3, and 5 have considerable growth potential in the lunar landing mission area.

Sun synchronous payload emplacement requires only a small delta-V, but the amount of payload that can be injected depends upon shuttle payload capacity to low earth orbit at an inclination of about 100 degrees. For this mission, it is assumed that the space tug, payload, and propellant are delivered by the EOS to 100 degrees and 100 n mi (185 km), and the tug conducts a coplanar mission to the desired altitude. The data shown are for a

Table 3. Growth Potential and Versatility (Payload Within Mission Categories) (1000 lb)

CONCEPT	LOW EARTH ORBIT	OUTBOUND GEOSYNCH		LUNAR LANDING		SUN SYNCH	PLANETARY			
							INNER		OUTER	
		1-STAGE (REC)	2-STAGE (REC)	TO SURFACE	ROUND TRIP		1-STAGE (REC)	2-STAGE (REC)	1-STAGE (EXP)	2-STAGE (2ND EXP)
1		10	48	87	35	2.2	13	54	8	23
2		-	22	46	20	4.9	1.8	26	3.3	12
3		-	17	97	40	5.5	-	20	2.3	10
5		-	10	75	30	6.3	-	13	1.0	6.8
11		10	20	59	23	9.8	12	24	2.4	12
COMMENTS	NOT SIGNIF.	CONCEPT 1 HAS CONSIDERABLE GROWTH CAP.		CONCEPTS 1, 3, & 5 HAVE GROWTH CAP.			• CONCEPT 1 ALLOWS SIMPLE SINGLE STAGE OPERATIONS FOR PLANETARY • OTHER CONCEPTS HAVE ADEQUATE CAPABILITY IN 2-STAGE MODES			

reference shuttle having 25,000 pound (11,300 kg) payload to 55 degree and 270 n mi (500 km). These data show that payload capability to sun synchronous increases with decreasing space tug size. This occurs because more propellant can be put into the smaller tugs in making up the total EOS capability. The concept 11 configuration utilizes only the small stage in accomplishing this mission, and it can emplace 9800 pounds (4450 kg) of payload.

All of the space tug concepts have adequate capability for the planetary missions, but concept 1 allows simple, single-stage missions to be conducted; and in the two-stage mode, it has the capability of injecting up to 54,000 pounds (24,500 kg) to the inner planets and 23,000 pounds (10,400 kg) to the outer planets.

Some alternate missions considered for the space tug include use as a cislunar shuttle, rescue in earth and lunar orbit, and roundtrip and return payload geosynchronous missions. Tug capabilities for these missions are shown in Table 4.

When used as a cislunar shuttle, the space tug has relatively low payload capabilities as compared to yearly resupply requirements which may be as high as 500,000 to 600,000 pounds (227,000 to 272,000 kg). Only concept 1 in the two-stage recoverable mode appears to have potential for

Table 4. Growth Potential and Versatility (Alternate Mission Capability)

CONCEPT	CISLUNAR PAYLOAD (1000 LB)		MAX. RESCUE ΔV (1000 FT/SEC)		GEOSYNCH P.L. (1000 LB)	
	1 STAGE (EXPENDED)	TWO STAGE (RECOVERED)	EARTH ORBIT	LUNAR ORBIT	ROUND TRIP (TWO STAGE)	RETURN (TWO STAGE)
1	41	52	22.4	22.4	12.5	16.8
2	25	28	23.7	18.2	5.6	7.6
3	22	23	22.5	22.5	4.4	5.9
5	17	15	20.5	20.6	2.5	3.3
11	27	27	18.3	18.3	5.1	6.8
COMMENTS	• ONLY CONCEPT 1 HAS POTENTIALLY ADEQUATE CAPABILITY		• CONCEPT 2 & 11 MARGINAL FOR WORST LUNAR CASE • ALL ABOUT EQUAL FOR OTHER SITUATIONS		• CONCEPT 1 CAN CARRY CREW MODULE ROUND TRIP • CONCEPT 1 CAN EMPLACE & RETRIEVE 10 K-LB PAYLOAD	

satisfying resupply requirements. Use of the space tug as a second stage (recoverable) on a large cislunar chemical shuttle also has been considered, but not parametrically. These studies indicate that the tug second stage improves the payload to propellant ratio for the cislunar mission by a factor of nearly two.

The maximum delta-V available for the space tugs in their normal lunar configuration (but without landing legs) and in their normal geosynchronous mission configuration for earth orbit also is shown in the table. A crew module weight about 10,000 pounds (4540 kg) is assumed to be carried as payload for these missions. Consideration of all lunar abort and rescue situations has indicated that the worst condition is an abort from the surface to low earth orbit, requiring a delta-V of about 19,600 ft/sec. Only concepts 2 and 11 are marginal in accomplishing this mission. However, these concepts can get into a fairly low elliptical or circular earth orbit. All of the concepts have comparable capability in low earth orbit, and no specific requirement has been identified for performance in low earth orbit, but rather, the best possible has been the criteria.

Finally, in the geosynchronous area, concept 1 has superior capability and in the two-stage configuration can carry a crew module roundtrip, thus allowing for manned mission capability to geosynchronous orbit. Furthermore, concept 1 can emplace and retrieve a 12,500-pound (5700-kg) satellite in a single trip. All other concepts have considerably less capability.

In this category, it is concluded that concept 1 has superior growth potential and versatility when compared to the other concepts.

Operations Complexity

Table 5 presents data related to operational complexity for each of the concepts. Three categories are considered: mission success (which is related to the number of modules utilized in the mission), space operations complexity (which is related to the number of dockings for staging the mission), and the number of EOS launches required to complete the operation.

As an example of the mission success category for the low earth orbit support mission, only the crew, intelligence, and propulsion modules are used in a single-stage operation for all concepts. No differences exist among the various concepts in this category. Because only a single stage and IM is used for concept 1 in the geosynchronous mission, it is superior to all the other concepts that utilize either a tank set in addition to these items (concepts 2, 3, and 11) or another propulsion module and IM (concept 5). The differences in the lunar landing mission for concepts 3, 5, and 11 are caused by the tank set required for these concepts.

Table 5. Operations Complexity

CONCEPT	NO. OF MAJOR MODULES			SPACE OPERATION COMPLEXITY (NUMBER OF DOCKINGS)				INTEGRAL EOS LAUNCHES (NO. OF EOS LAUNCHES)			
				GEOSYNCH					GEOSYNCH		
	LOW EARTH ORBIT	GEO-SYNCH	LUNAR LANDING	GRD BASED	SPACE BASED (NO PF)	SPACE BASED (PF)	LUNAR LANDING (EO ASSY)	LOW EARTH ORBIT	GRD BASED	SPACE BASED (NO PF)	LUNAR LANDING (EO ASSY)
1	3	2	6	4	4	2	3 (M)	1	4	3	2
2	3	3	6	5	4	2	3 (M)	1	6	3	2
3	3	3	7	5	4	2	4	1	6	3	2
5	3	4	7	4	5	5	4	1	3	3	2
11	3	3	7	2	3	2	3 (M)	1	2	2	2
COMMENTS	• CONCEPT 1 BEST			• CONCEPT 11 BEST • CONCEPTS 2 & 3 REQUIRE TANK SET SPACE ASSEMBLY				• CONCEPT 11 BEST • CONCEPTS 2 & 3 REQUIRE LARGE NO. OF LAUNCHES FOR GROUND-BASED GEO MISSION			

The number of docking operations and the number of EOS launches for the missions were determined from a step-by-step analysis that assumed the baseline shuttle with a 25,000-pound (11,300-kg) payload capability to 55 degrees and 270 n mi (500 km). For the geosynchronous mission, these include all of the operations necessary to get the tugs to orbit and back to the surface in the ground-based cases and to get the propellant and payload to orbit for the space-based cases. For the lunar landing mission, the operations included only those necessary to bring the necessary modules to earth orbit and to assemble the modules in earth orbit. The operations in lunar orbit were considered to be similar for all of the concepts and are not included in these numbers. In the lunar landing column, the M in parenthesis means that all operations involve the mechanical mating of systems such as landing gear and cargo modules. Those without the M involve more complex on orbit matings, which for concepts 3 and 5 involve mating of a tank set on orbit. Mechanical, electrical, and fluid couplings are required in this case. Concept 11 is the best in all categories of space operations complexity.

The number of EOS launches required for ground-based operations is related to the lengths of the concepts as well as their propellant capacities. If the lengths of the integrated configurations exceed the EOS bay length, they have to be carried to and from orbit separately. This is the case for concepts 2 and 3, which require 6 EOS launches to complete the mission.

Concept 11 is superior in this category, because it is compact and requires less propellant than the other concepts. All concepts are equal for lunar mission earth orbit operations in this category.

Risk

The only factor considered in the evaluation of risk was the potential influence of weight growth on cost per mission and the ability to bring the propulsion module, intelligence module, and, if necessary, the crew module to orbit assembled in the EOS with a 60-ft (18.3 m) bay length. Table 6 summarizes the data in this category. Based on sensitivity data, if the weight growth per stage for a two-stage concept is the same as the weight growth of a larger single-stage configuration, the total growth in propellants for both stages of a two-stage configuration is the same as the propellant growth for a single-stage configuration. If this is assumed, then both the one and two-stage concepts have the same mission cost increase because of propellant resupply costs.

Table 6. Risk Data Summary

CONCEPT	WEIGHT GROWTH (+1000 LB/STAGE)				
	COST PER MISSION			FIT EOS BAY?	
	LOW EO	GEOSYNCH	LUNAR LANDING	GEOSYNCH	LUNAR LANDING
1	← NOT SIGNIFICANT →	$1.5 M (+10 K PROP)	$2.6 M (+4 K PROP)	YES (52 FT)	MARGINAL (60 FT)
2		GREATER RISK THAN 1	$2.6 M (+4 K PROP)	NO (69 FT)	YES (46 FT)
3		GREATER RISK THAN 1	GREATER RISK THAN 1	NO (69 FT)	NO (77 FT)
5		$1.5 M (+10 K PROP)	GREATER RISK THAN 1	MARGINAL (60 FT)	NO (65 FT)
COMMENTS	• SINGLE & TWO-STAGE GEOSYNCH CONCEPTS HAVE SIMILAR WEIGHT GROWTH/STAGE • CONCEPTS WITH STAGE & TANK SET HAVE POTENTIALLY GREATER RISK			• ALL VERSIONS WITH STAGE & TANK SET REQUIRE SPACE ASSEMBLY • LARGE SINGLE-STAGE MARGINAL • TWO-STAGES BROUGHT UP SEPARATELY	

Concepts 2 and 3 operate like a single-stage configuration for the geosynchronous mission but are comprised of a stage and a tank set. Because this is a more complex system than a simple single-stage system, it is considered that the weight growth in the stage and the tank set is likely to be greater than for the simple single-stage concept.

As noted previously, concepts 2 and 3 did not fit into the bay of the shuttle even without additional growth, and, therefore, the tank set and propulsion module have to be assembled on orbit for the geosynchronous mission. Concept 1 does fit into the bay for the goesynchronous or lunar landing mission. The two stage geosynchronous concept (concept 2) is marginal for the geosynchronous mission and the two stages may have to be carried up separately and mated on orbit. The operation of mating on orbit is, however, operationally necessary normally for this concept. In the lunar landing configuration, concept 5, with the crew module attached, is too large, and the crew module would have to be mated on orbit, which is a relatively complex operation.

As a result of the risk evaluation, it has been concluded that the simple single-stage concept (concept 1) and the two-stage concept (concept 5) have similar propellant growth risk for the geosynchronous mission; although a much more detailed design analysis of the systems is necessary to fortify this conclusion. Based on the complexity of the stage plus tank set concepts (concepts 2 and 3), it is anticipated that they would have even greater growth risk. The stage-plus-tank set versions also are too long to fit into the EOS bay and therefore must be assembled on orbit. Concept 11 was not formally evaluated in this area because of its late introduction, but it is obvious that it can fit into the EOS even with weight growth because it is relatively compact.

Economic Comparison of Lunar Landing Modes

An economic comparison of three lunar landing modes (modes A, B, and C) are shown on Table 7. In mode A, 20,000 pounds (9100 kg) of payload are delivered by the space tug both to the surface and back to lunar orbit. Of this payload, about 10,000 pounds (4540 kg) is the crew module. This mode allows any-time abort along the descent profile and also allows a generous margin for returning payload to orbit that did not have to be consumed on the surface, such as rovers, flyers, and experiments.

Mode B systems are designed for a 20,000-pound (9100-kg) payload to the surface and a 10,000-pounds (4540-kg) payload returned to orbit. This mode implies a commitment to land when abort occurs near the surface, or alternatively, jettisoning of the 10,000-pounds (4540-kg) payload to allow abort to orbit. This mode allows the return of only a small amount of payload (in addition to the crew module) to lunar orbit.

Table 7. Economic Comparison of Lunar Landing Modes

CONCEPT	LUNAR LANDING MODE		
	MODE A (20 K DWN/20 K UP) $\bar{M}$/MISSION	MODE B (20 K DWN/10 K UP) $\bar{M}$/MISSION	MODE C 10 K DWN/10 K UP) $\bar{M}$/MISSION
1	44.5	38.8	64.9
2	39.0*	-	-
3	45.5	33.0	57.7
4	-	31.5*	-
5	43.6	37.2	56.0*

*OPTIMIZED CONCEPT FOR THIS MODE

Mode C requires two tug flights to the surface to conduct a mission. Both carry 10,000 pounds (4540 kg) to the surface separately, one carrying the crew module and the other the surface payload.

These data show that Mode C increases mission costs by about 43 percent as compared to mode A. The flexibility in mission operations provided by mode A increases the mission cost by 15 percent. Because the costs shown for mode A assume that the 20,000 pounds (9100 kg) are carried roundtrip, the mode A cost would be lower if, on a normal mission, only 10,000 pounds (4540 kg) are returned to orbit and the tug is loaded with propellant as if 20,000 pounds (9100 kg) would be carried to allow any-time abort. Under these circumstances the tug would return to orbit with propellant remaining, which could be used on a subsequent mission.

These data also show the penalty for off-loading an oversized tug to accomplish these missions. As an example for mode A, concept 1, which can hold 80,000 pounds (36,300 kg) of propellant and is off-loaded for this mission, costs only 14 percent more per mission.

PHASE I RECOMMENDATIONS

As a result of the Phase I studies and the evaluation of the several propulsion module concepts, it was recommended that the following concepts be selected for the Phase II studies: (1) the large single-stage concept (concept 1) originating from the geosynchronous mission, (2) concept 5, the concept which originates from the recoverable two-stage geosynchronous mission, and (3) concept 11, which was designed to accomplish the geosynchronous mission in a mode that requires expenditure of a tank set when the payload is injected.

It was also recommended that the vertical cylinder crew module be selected over the horizontal cylinder crew module. A comparison of these two approaches indicated that the volume allocation for the vertical cylinder was slightly greater than for the horizontal cylinder, when both are constrained by EOS cargo bay limitations when attached to the propulsion and intelligence modules. The EOS bay constraint also resulted in similar functional arrangements of the two concepts. The primary reason for selecting the vertical cylinder is the ease in which two vertical cylinders are integrated together as compared to integrating a vertical cylinder IM and PM with a horizontal cylinder crew module.

The more detailed studies of Phase II were required for selecting the intelligence module approach, and no specific recommendations were made at the conclusion of Phase I.

PHASE II SUMMARY

A logic diagram depicting the relationship of the studies conducted during the second phase of the contract is shown in Figure 33. The three concepts selected as a result of the Phase I studies were studied in greater detail to refine the mission and operations data related to their use (including implications of ground and space basing on operations and performance and the definition of their capabilities for performing all of the integrated program plan mission objectives). The mission and operations refinement studies resulted in the determination of program buildup data, performance data, and operational tradeoff data, which were used in the refinement of the concepts, to establish the planning data, and to develop economic tradeoff data comparing these concepts.

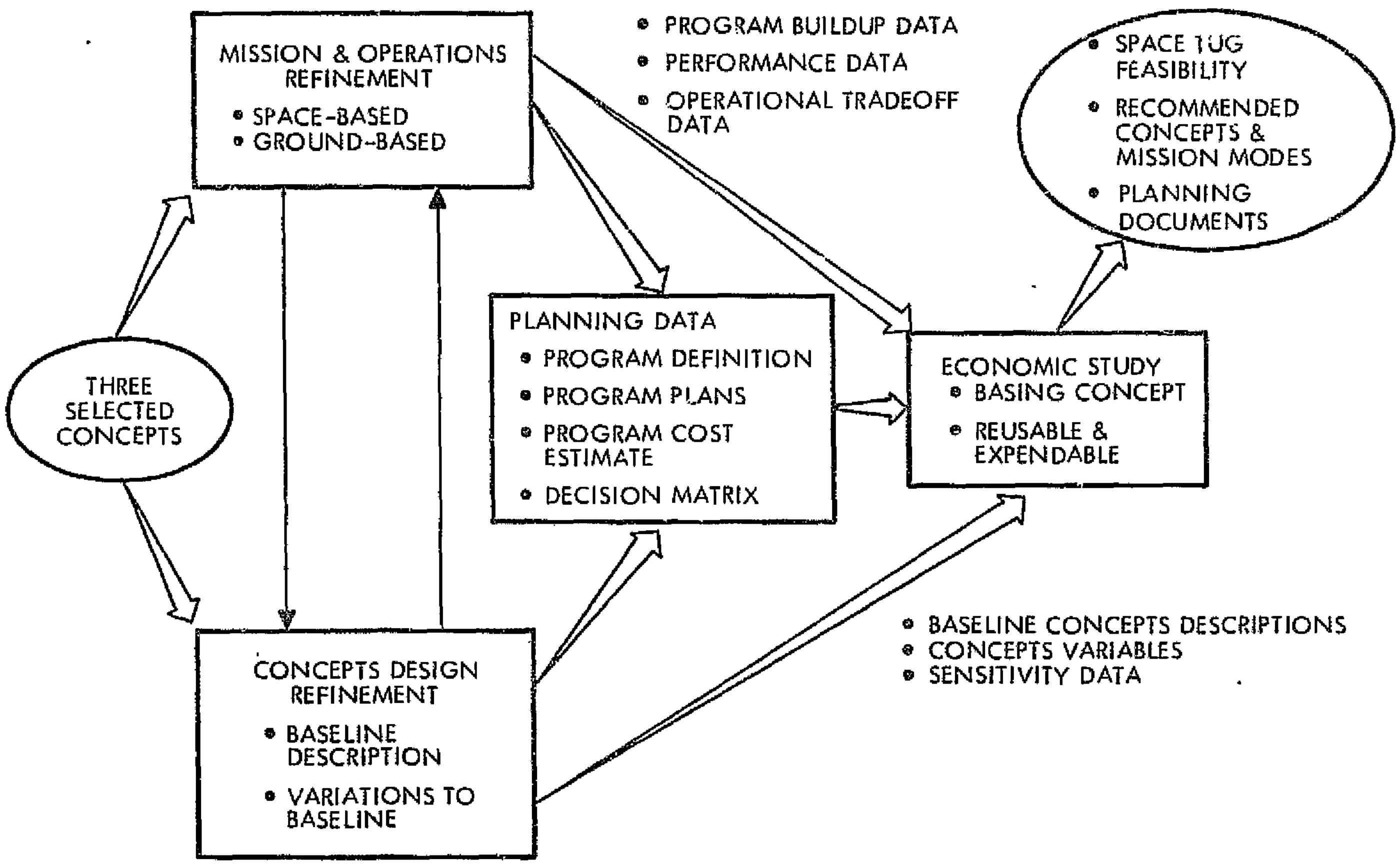


Figure 33. Phase II Studies

The design refinement studies were directed toward a more critical examination of the design characteristics of the concepts. These included layouts of the various modules (including placement of subsystems and module interfaces), several key subsystem tradeoff studies, and an estimation of the effects of changes to a baseline concept on mass properties and concept size. These data were utilized in the mission and operations refinement studies to relate performance sensitivity to concept variations. They also were used as a baseline to produce the planning data and to assess the relative economics of the concepts and the influences of variations in the baseline on space tug economics.

The economic study resulted in comparisons of the reusable concepts in performing the matrix of missions and sensitivity of these results to variations in the baseline concept characteristics and mission characteristics, including the impact of shuttle payload capability and propellant resupply costs. Comparisons also were made between the reusable and expendable concepts for accomplishing the high-performance geosynchronous mission.

The results of the studies then were analyzed to determine the feasibility of the space tug concept, to recommend feasible concepts and mission modes, and to provide planning data for future program phases.

The Phase II technical discussion is organized in the following manner:

Concepts Descriptions. The three selected concepts baseline characteristics and deviations from the baseline are described.

Reusable Concepts Comparisons. The characteristics of the baseline concepts are compared in an evaluation similar to that conducted during Phase I.

Space Tug Evolution. The several factors influencing the characteristics of the tug are analyzed and potential approaches for evolution of the tug are described.

Comparisons of Tug and Other Systems. The space tug is compared to other potentially competitive systems in each mission area.

CONCEPTS DESCRIPTION

During the initial portion of Phase II, the three selected concepts were resized, based on refined subsystems and design data, to accomplish the 10,000-lb (4540-kg) geosynchronous payload insertion mission. The results

of this resizing of the baseline concepts are shown in Figure 34. This figure shows the propellant capacity, gross weight (including the 10,000-lb or 4540-kg payload), and the length of the propulsion and intelligence modules when organized to accomplish the geosynchronous injection mission. The resizing resulted in a slight reduction in size for concept 1, an increase in size for concept 5, and an increase in size for concept 11.

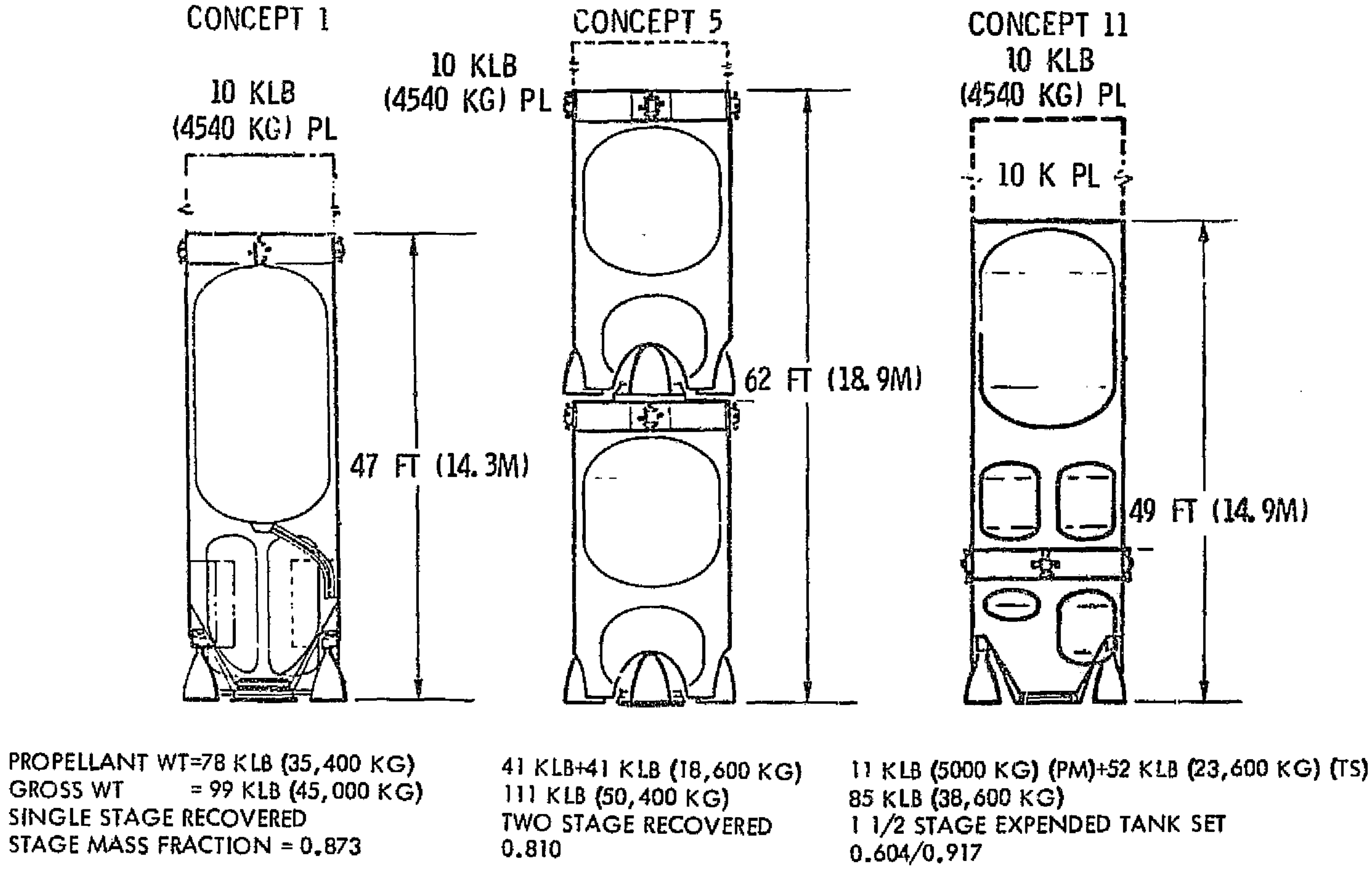


Figure 34. Reusable Geosynchronous Mission Space Tug Concepts

Table 8 summarizes the weights of the propulsion and intelligence modules for the baseline concepts that were sized for the geosynchronous equatorial mission. As shown, the intelligence module comprises a large percentage of the total system inert weight. Concept 11 has the lowest gross weight and requires the least propellant because of the expenditure of the tank set upon insertion of the payload at geosynchronous equatorial conditions.

Table 9 lists the staging arrangements of the selected reusable concepts in accomplishing the various mission categories. Only concept 1 is capable of accomplishing all of the missions in a single staging (single stage) relationship. Concept 5 varies from single stage for low earth orbit missions to two-stage for the high-energy missions. It requires the addition of a tank set of capacity equal to the stage to accomplish the lunar landing mission. Concept 11 requires the expenditure of a tank set for the high-energy missions. The combination of the propellant capacity provided by the small stage and tank set is sufficient to accomplish the lunar landing missions while still recovering all flight hardware.

Table 8. Concept Weight Summary for Geosynchronous Equatorial Mission (Start From and Return to 100-n mi Orbit)

CONCEPT	NO. 1	NO. 5		NO. 11	
ELEMENT \ STAGING	RECOVERABLE SINGLE STAGE	RECOVERABLE TWO STAGE SLINGSHOT MODE		1 1/2 STAGE TS LEFT AT GEO, PM RECOVERABLE	
DRY WEIGHT POUNDS (KG)	9075 (4110)	7885 (3580)	7885 (3580)	6170 (2800)	3520 (1600)
IM	3380	3380	3380	3380	
PM~4 ENGINES	5695	4505	4505	2790	
TS~NO ENGINES					3520
NON IMPULSIVE FLUIDS	2000 (900)	1180 (540)	1700 (770)	565 (260)	1395 (630)
RESIDUALS	990	885	885	235	715
INFLIGHT LOSSES*	370	185	185	185	185
AUX PROPELLANTS**	640	110	630	145	495
IMPULSIVE PROPELLANT	77,975 (35,400)	41,210 (18,700)	41,210 (18,700)	10 980 (4970)	52,375 (23,800)
PAYLOAD	10,000 (4540)	10,000 (4540)		10,000 (4540)	
GROSS WEIGHT AT IGNITION	99,050 (45,000)	111,070 (50,400)		85,005 (38,600)	

*INCLUDES START, SHUTDOWN & BOILOFF LOSSES

**INCLUDES EPS & ACPS

Table 9. Staging Arrangements of Reusable Concepts

CONCEPT	PROPELLANT LOADING 1000 LB (1000 KG)	STAGING ARRANGEMENTS: GEOSYNCH	LUNAR LANDING	LOW EARTH ORBIT	PLANETARY: INNER	PLANETARY: OUTER
1	78 (35)	SINGLE STAGE	SINGLE STAGE	SINGLE STAGE	SINGLE STAGE	~~SINGLE STAGE~~
5	41 (19)	TWO STAGE	STAGE & TANK SET	SINGLE STAGE	TWO STAGE	~~TWO STAGE (SECOND EXP)~~
11	11/52 (5/24)	~~SMALL STAGE & TANK SET (TS EXPENDED)~~	SMALL STAGE & TANK SET	SMALL STAGE	~~SMALL STAGE & TANK SET (TS EXPENDED)~~	~~SMALL STAGE & TANK SET (BOTH EX-PENDED)~~

The primary design characteristics of the three basic modules (propulsion, intelligence, and crew) are shown in Figure 35 along with the reasons for the design characteristics. A more detailed view of concepts 1 and 11 is shown in Figure 36. The propulsion module has four high chamber pressure engines located around a central aft Apollo-type docking gear. The four engines provide redundancy with an engine out and also help to reduce stage length. The single hydrogen tank allows the simplest, lowest weight, and least length packaging arrangement. The four oxygen tanks were selected on the basis of their integration with the four engines. They allow common load paths for the engines and oxygen tanks. The structure is nonintegral, although integral structure was considered as an alternative.

The intelligence module is designed for autonomous space-based operations, and the baseline is a completely modular system. This module contains all of the components necessary to conduct unmanned missions when combined with the propulsion module or to conduct manned missions when combined with the propulsion module and crew module. The general location of avionics equipment in this module also is shown on this figure. All of the equipment is not shown for simplicity. A more detailed layout is shown in Volume 4. Because the baseline system assumes space basing, more than one level of redundancy is provided for some of the key components to assure that the missions may be accomplished with little or no servicing being required.

The baseline crew module is a vertical cylinder of 15 feet (4.6m) in diameter and 8 feet (2.4m) in height. The free volume is sufficient for a 4-man, 28-day lunar surface mission and is oversized for routine, low earth orbit space station support missions.

The baseline design is not necessarily optimum, and several variations to this design (shown in Table 10) have been considered to establish their effect on gross weight, length, operational characteristics, and other factors. Several of the variations are specifically design-oriented, such as, number of engines, number of LO_2 tanks, docking gear, and PM structure. Others are operational variations that influence design, such as basing and autonomy. Although earth orbital shuttle and space station technology has been assumed for the baseline, the impact of utilizing more advanced (but realizable) technology has also been considered.

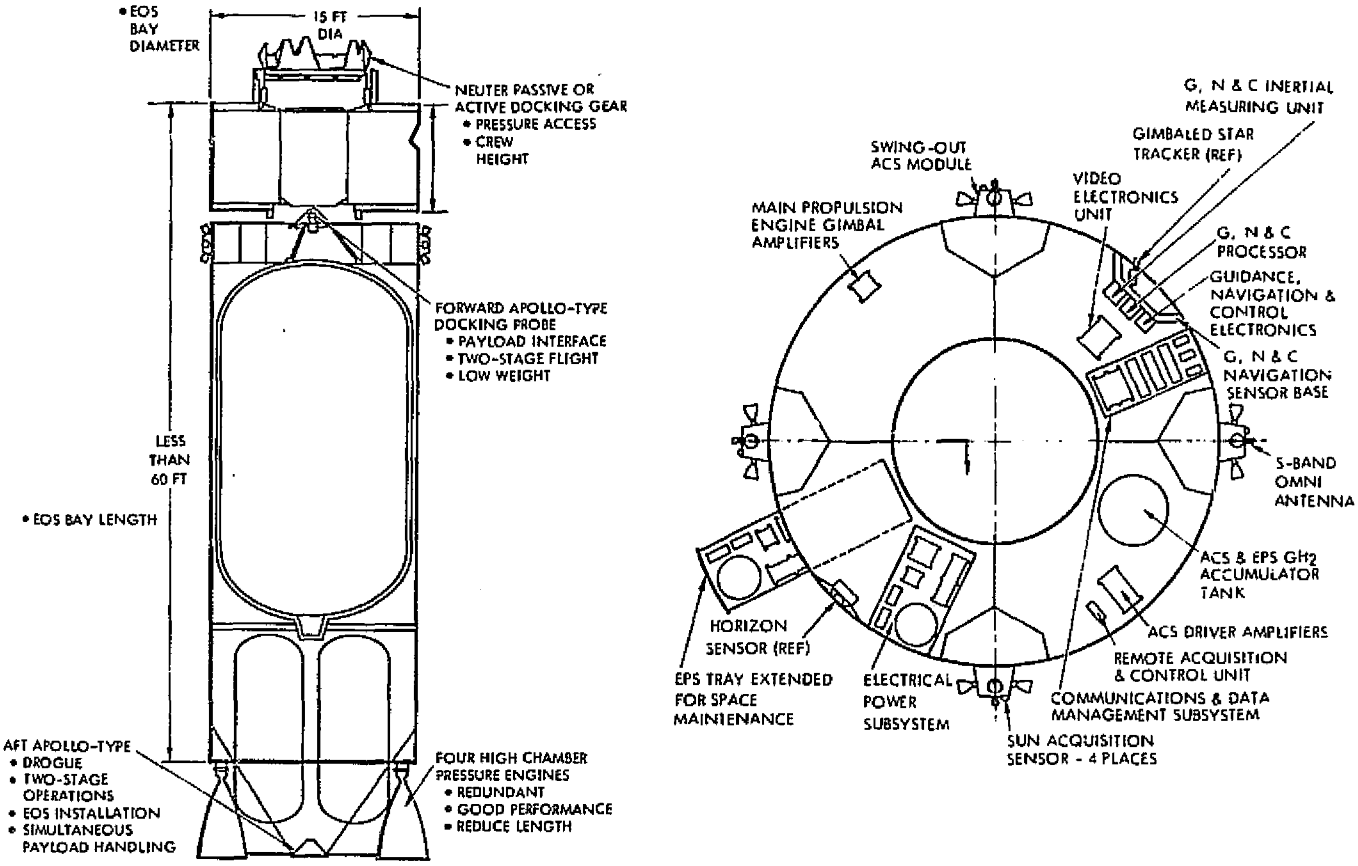


Figure 35. Derivation of Baseline Conceptual Features

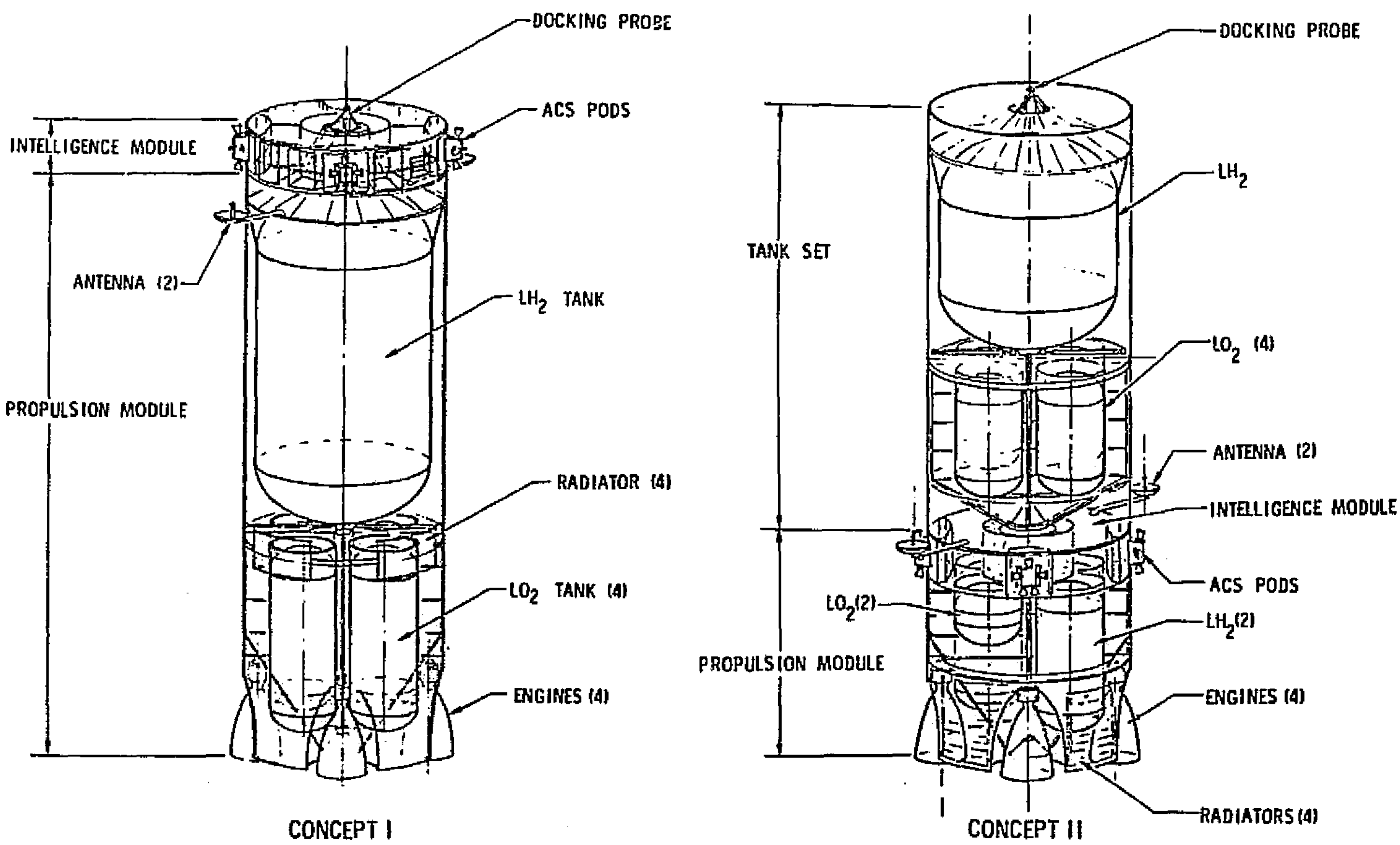


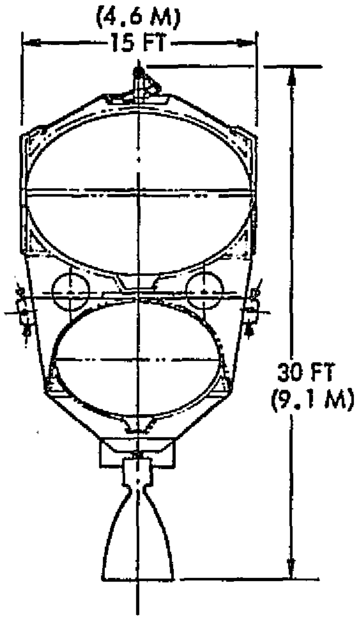
Figure 36. Concept Detailed Design Characteristics

Table 10. Variations to Baseline

VARIATIONS	PRIMARY DESIGN INFLUENCES			
	INERT WEIGHT	LENGTH	SPECIFIC IMPULSE	OTHER
NUMBER OF ENGINES - 1, 2, 4*	✓	✓	✓	DOCKING GEAR & O_2 TANK ARRANGE.
BASING - SPACE-BASED WITH PF, SPACE-BASED (EOS FUELING), GROUND-BASED	✓ (INSULATION & REDUNDANCY)			EOS INTERFACES. OVERALL OPERATIONS
TANKAGE - 1, 2, 4 LO_2 TANKS	✓	✓		NUMBER & ARRANGE. OF ENGINES
DOCKING GEAR - APOLLO-TYPES, NEUTER (ACTIVE, PASSIVE), OTHER	✓	✓		NUMBER OF ENGINES & INTERFACES WITH OTHER IPP ELEMENTS
IM MODULARITY - TOTALLY MODULAR, MODULAR AVIONICS, TOTALLY INTEG	✓			IM USES, SERVICING
AUTONOMY - MAXIMUM AUTONOMY, MODERATE AUT, NONAUT	✓			MISSION SUPPORT & MISSION CAPABILITY
TECHNOLOGY BASE - EOS/SPACE STN, ADVANCED TECHNOLOGY	✓		✓	
PM STRUCTURE - NON-INTEGRAL, INTEGRAL	✓			INSULATION APPROACH

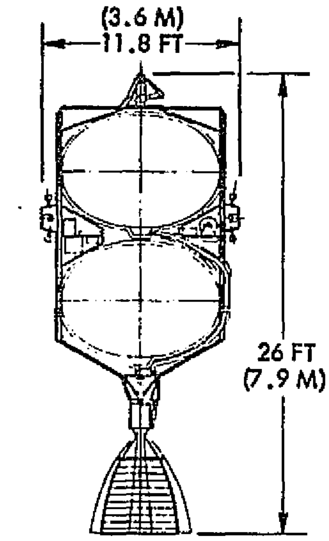
*INDICATES BASELINE

Two concepts, specifically designed for a single stage, expendable geosynchronous mission mode, also were considered to allow a comparison with the reusable modes for this mission. The characteristics of these two concepts, one a LO_2/LH_2 stage and the other an earth storable A-50/N_2O_4 stage are shown in Figure 37. The LO_2/LH_2 stage has separate tankage to minimize boiloff during ascent in the EOS. Installation in the shuttle is accomplished by picking up structure that supports the oxygen tanks and through a sleeve around the engine and into the rear thrust structure. This sleeve is connected to the docking gear of the EOS to allow removal on orbit. The A-50/N_2O_4 stage shown in this figure has separate tankage for simplicity and has to be installed in the EOS in a manner similar to the LO_2/LH_2 stage. Avionics components in these stages are considerably simpler than the baseline tug, and ground tracking and command is necessary to accomplish the missions. Provision for more autonomy would result in a prohibitive stage unit cost for expendable stages.



LO_2/LH_2

BURN-OUT WT	6200 LB (2810 KG)
MAIN PROPELLANT WT	27,300 LB (12,400 KG)
PAYLOAD WT	10,000 LB (4,540 KG)
GROSS WT	44,030 LB (20,000 KG)
STAGE MASS FRACTION	0.795
I_{SP}	463 SEC



$A\text{-}50/N_2O_4$

BURN-OUT WT	5300 LB (2400 KG)
MAIN PROPELLANT	46,000 LB (20,900 KG)
PAYLOAD WT	10,000 LB (4,540 KG)
GROSS WT	60,900 LB (27,600 KG)
STAGE MASS FRACTION	0.905
I_{SP}	325 SEC

Figure 37. Expendable Stage Characteristics

REUSABLE CONCEPTS COMPARISONS

During the Phase II refinement studies, the data utilized to select concepts during the first phase of the study were reexamined and updated as necessary. Information in this section will be presented in a format similar to that previously presented for the Phase I evaluation.

Basing Considerations

Prior to comparing the selected concepts, it is necessary to discuss basing options because of their influence on operations. Three basing options have been considered: (1) ground-based, (2) space-based without a propellant facility, and (3) space-based with a propellant facility.

The ground-based concept is illustrated in Figure 38. For this concept, the tug mission is initiated on the ground, and, following completion of the mission, the tug is returned to the ground. On the first EOS flight, the tug is brought up with the payload attached and partially fueled up to the payload capacity of the EOS. Subsequent EOS flights bring up the additional propellants required for the mission, with the EOS transferring the fuel directly to the tug on orbit. During the last propellant transfer mission, the EOS remains on orbit while the tug delivers the payload to geosynchronous orbit and returns. The tug is then returned to the earth's surface in the shuttle

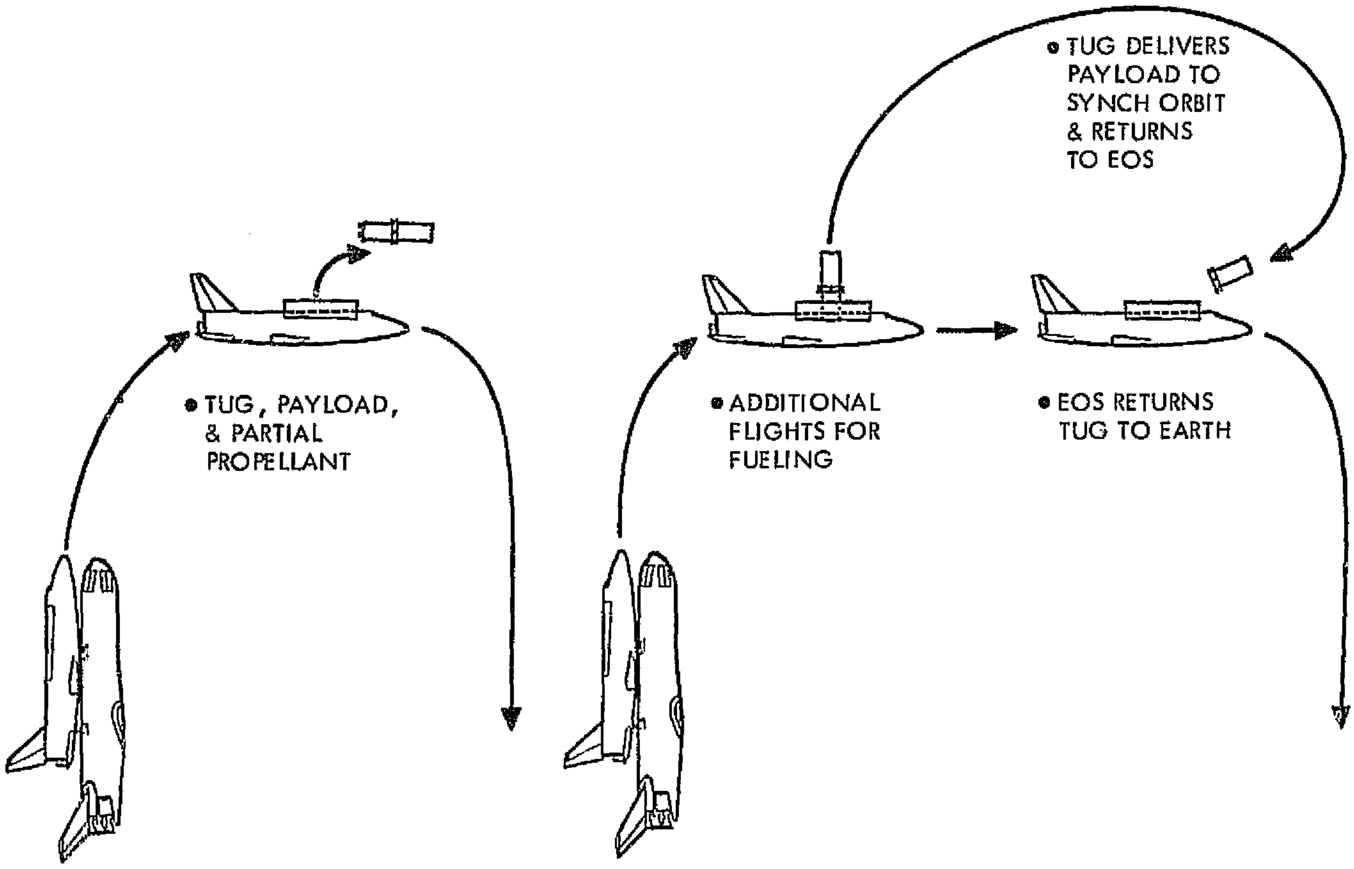


Figure 38. Ground-Based Geosynchronous Tug Operations

bay. It should be noted that return of the tug in this EOS is contingent upon sufficient space being available in the bay. Because of this constraint, it may be necessary for the EOS to return to the surface for disposal of the propellant tanks prior to recovery of the tug. This may require one or more additional EOS launches, depending upon shuttle bay size and payload capacity as well as tug concept (for example, single stage, two-stage, or stage and one-half). If more than one EOS is used on these missions, the number of EOS launches also may be affected (e.g., the second EOS may not have a propellant container and can remain on orbit to recover the tug).

For sufficiently large EOS sizes, the mission is accomplished in a single flight with the payload integrated and the tug fully fueled. Ground basing also has a significant impact on subsystems requirements and stage insulation concepts. Ground basing requires less redundancy and memory in the avionics because of the capability to checkout, replace, and reprogram the system on the ground following each mission. Because it is required to carry the tug to orbit with propellants, the ground-based insulation scheme must provide for rapid venting of the multilayer insulation during launch and while on orbit to avoid excessive boiloff. It also must avoid the problem of internal liquification of trapped gases on the ground during ascent.

The space-based operational mode that utilizes the EOS directly as a tanker is illustrated in Figure 39. In this operational mode, the first mission is accomplished in a manner similar to the ground-based mission, except that the tug remains on orbit following mission completion. Several subsequent missions are accomplished by refueling the tug on orbit by the EOS and by docking with the payload brought up by the EOS. As necessary, the tug is brought back to the earth's surface for major refurbishment.

The number of EOS flights required for mission accomplishment depends upon EOS payload capability, space tug concept, and the number of space tugs in operation on orbit. If only one space tug is in operation, an integral number of launches of the EOS are required for each mission. If two space tugs are in operation, one of the tugs is considered to be the mission tug, and the second is used to store excess propellants brought up by the EOS. The two tugs are used alternatively to accomplish the required missions. The later scheme always utilizes the full payload capacity of the EOS. The efficiency of the two-tug scheme is comparable to space-based operation with a propellant facility, which is discussed in the next paragraph.

Space-based operations with a propellant facility are shown in Figure 40. In this operational mode, the tug initially brought to orbit by the EOS, is stationed at an orbiting propellant facility. The EOS routinely refuels the propellant facility and brings payloads to low orbit. The tug is refueled from the propellant facility for each mission and returns to the earths surface in the EOS for major refurbishment. Alternatively, the tug may transfer the propellant from the EOS at 100 n mi (185 km) to the propellant facility at a higher orbital altitude to increase the net EOS payload at the propellant facility. The later mode is the one that has been assumed in the operations and economic studies.

Economics

Calculation of the relative program costs of the three reusable concepts was accomplished in a manner similar to that previously described for the Phase I evaluation. However, the design, development, test, and engineering (DDT&E) nonrecurring costs were recalculated based on a better definition of the space tug program. First unit costs also were revised for the baseline concepts and are summarized below:

Propulsion module:

Concept 1 - $13.2 million

Concept 5 - $11.3 million

Concept 11 - $8.9 million

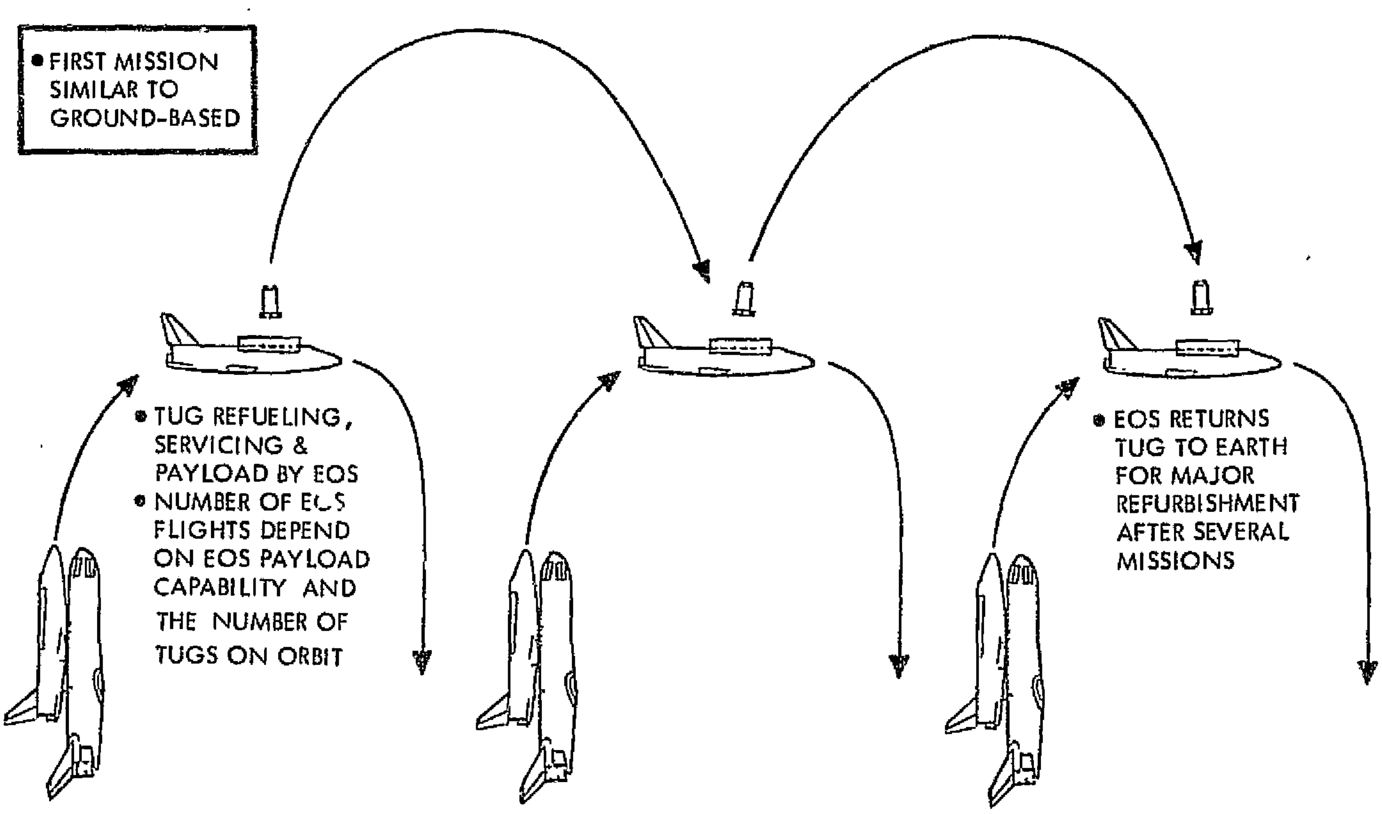


Figure 39. Space-Based Tug Operations With EOS Tanker

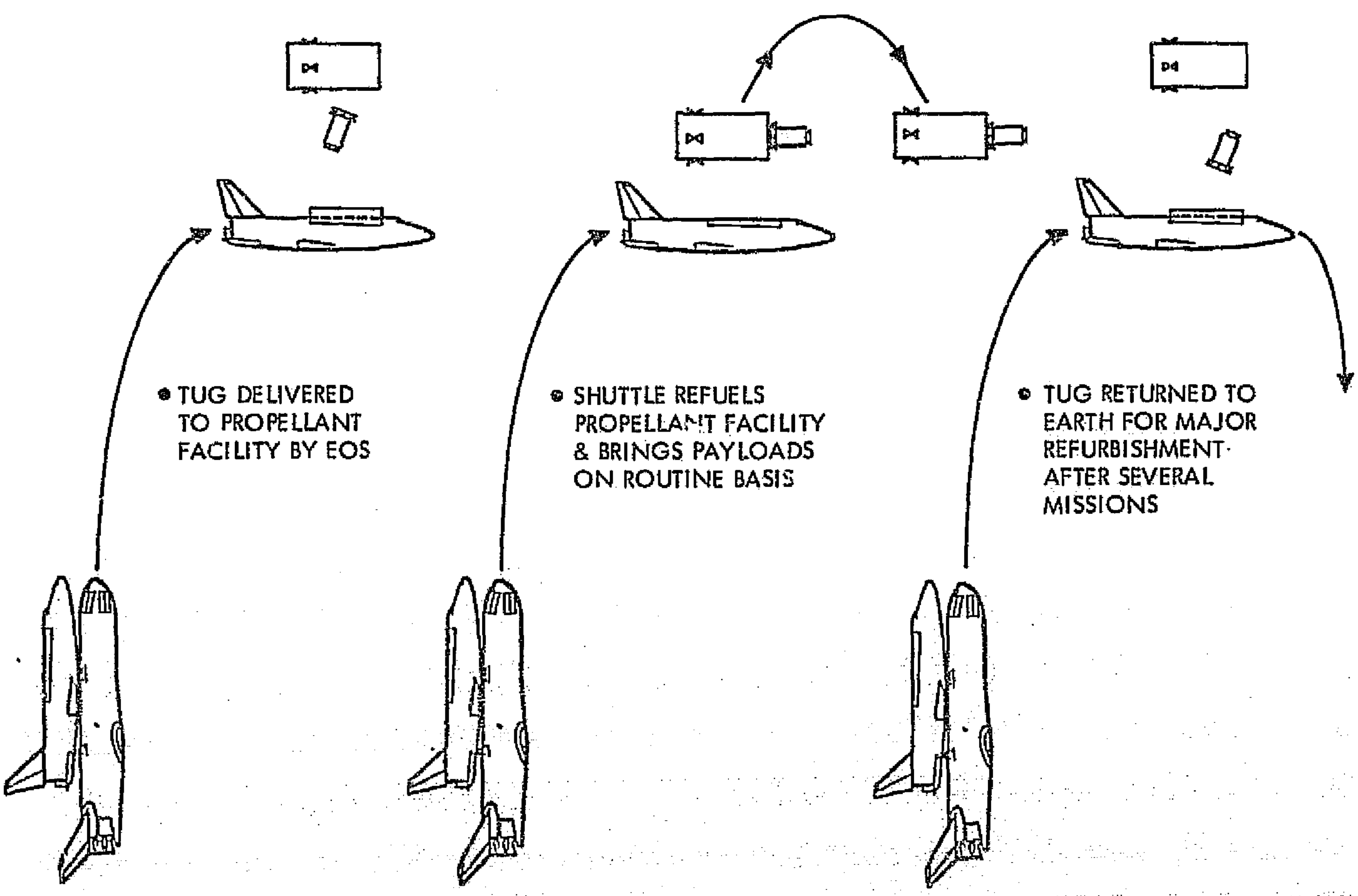


Figure 40. Space-Based Tug Operations With Propellant Facility

Tank set (concept 11) - \$6.7 million

Intelligence module (all concepts) - \$32.3 million

Crew module (all concepts) - \$18.8 million

Landing gear (all concepts) - \$2.2 million

The number of space tug reuses and the earth orbital and cislunar shuttle transportation costs were assumed to be the same as in Phase I. The unit costs shown previously are considered to be very conservative. As shown later in this document, when parametric data are presented, the unit cost is not significant as long as the number of tug uses are sufficiently high.

Figure 41 compares the 10-year program cost for the three space tug concepts across the entire spectrum of missions. The results are similar to those obtained during the first phase of the study — all concepts have comparable costs when all of the missions are considered. A comparison within mission categories shows differences between the concepts. Concept 1 is best in the geosynchronous category, concept 5 is best in the OSSA mission category, and concept 11 is best in the lunar and space station support categories. If the lunar mission category is eliminated, concept 11 has a higher total program cost than the others. In all cases, the DDT&E costs are similar. These comparative data for the geosynchronous mission were based on a propellant delivery cost of \$150 per pound (\$330/kg) and assumed that the recurring cost for hardware had no benefit from learning. Because concept 5 uses two PM's and two IM's for each mission and concept 11 expends a tank set for each mission, it would be expected that the effect of applying a learning curve would be to decrease the total cost for 11 significantly, to decrease the mission cost for concept 5 moderately, and to slightly decrease the mission cost for concept 1. The data shown in Figure 42 display this effect. The figures also show that concept 11 is less sensitive to propellant delivery costs.

Previous data were based on space-based operations. Figure 43 compares the average cost per mission for concepts 1 and 11 for ground-based geosynchronous operations and shows the effect of EOS payload capability on mission costs. The upper and lower bounds on the data show the effect of no learning and a 90-percent learning curve on cost. These data indicate that concept 1 is considerably lower in cost than is concept 11, but that concept 11 requires a smaller EOS payload capability (the break-points correspond to three, two, and one EOS flight required to conduct operations). Concept 5 is not shown because in a ground-based concept, an additional shuttle flight is required to conduct the mission because of its large length. Therefore, concept 5 is economically unattractive in the mode of operation.

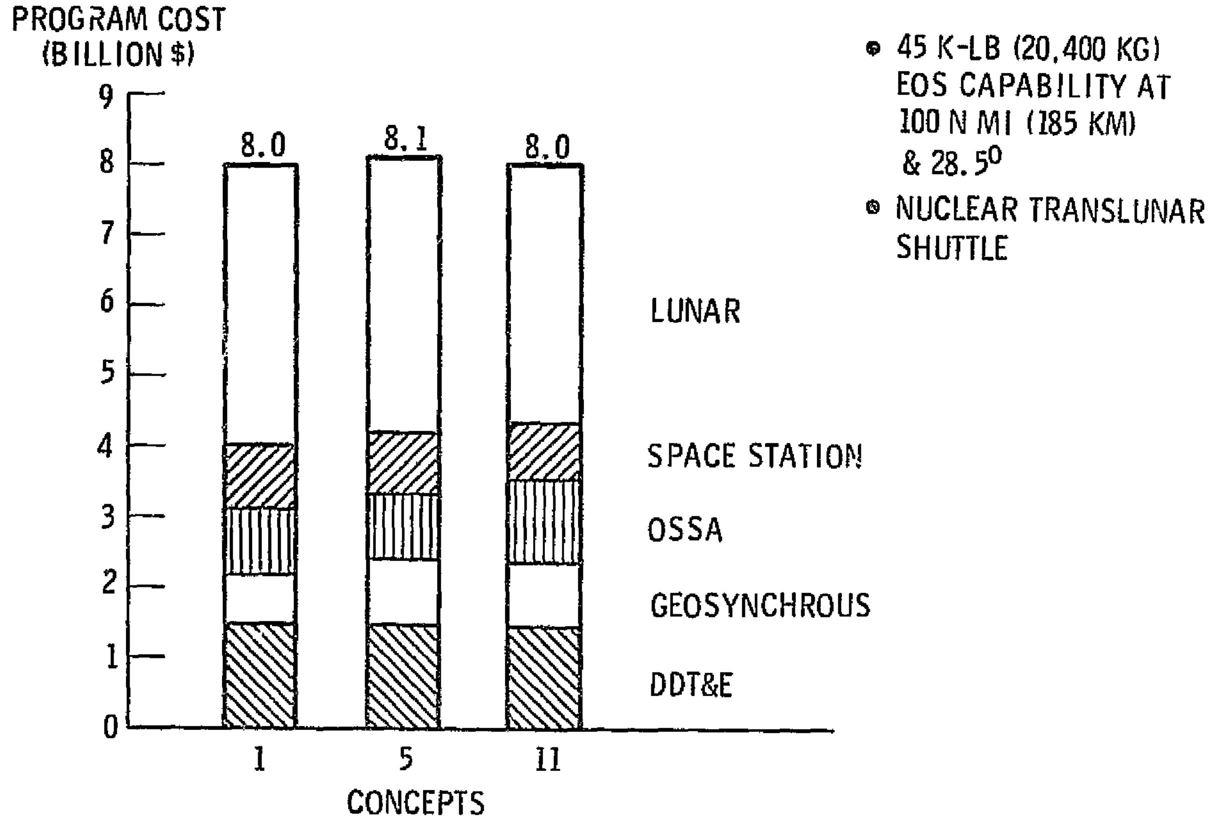


Figure 41. Space Tug (10-Year Total Space-Based) Program Costs

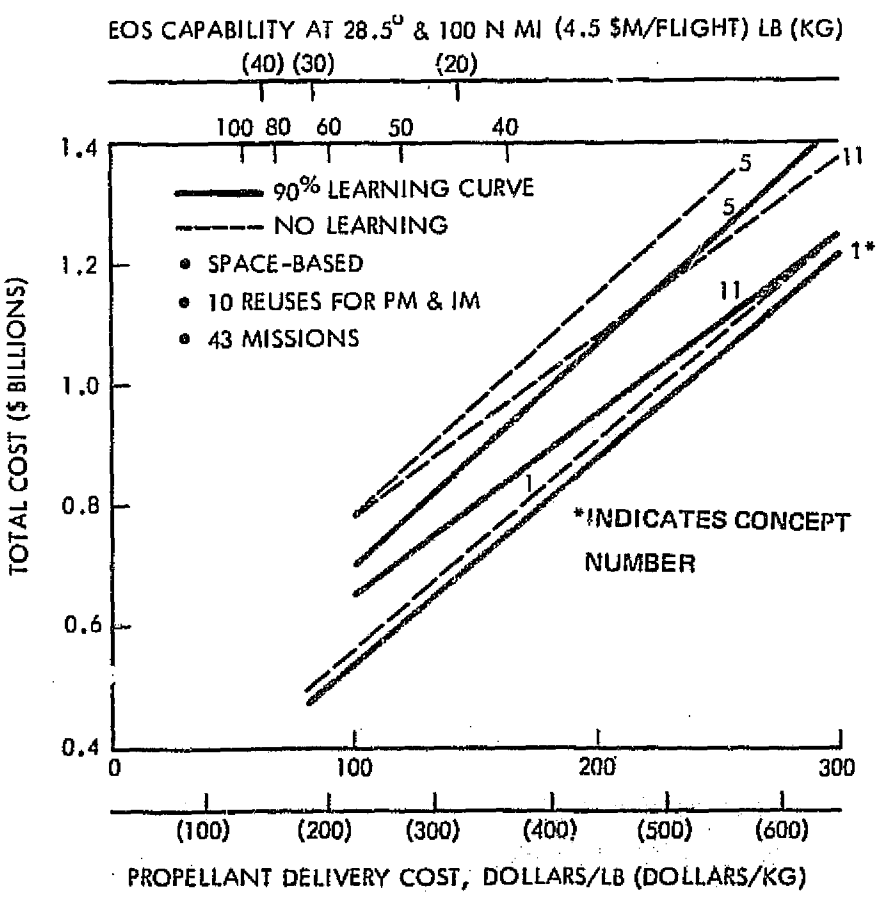


Figure 42. Effect of Propellant Deliver Cost and Learning Curve on Geosynchronous Program Cost

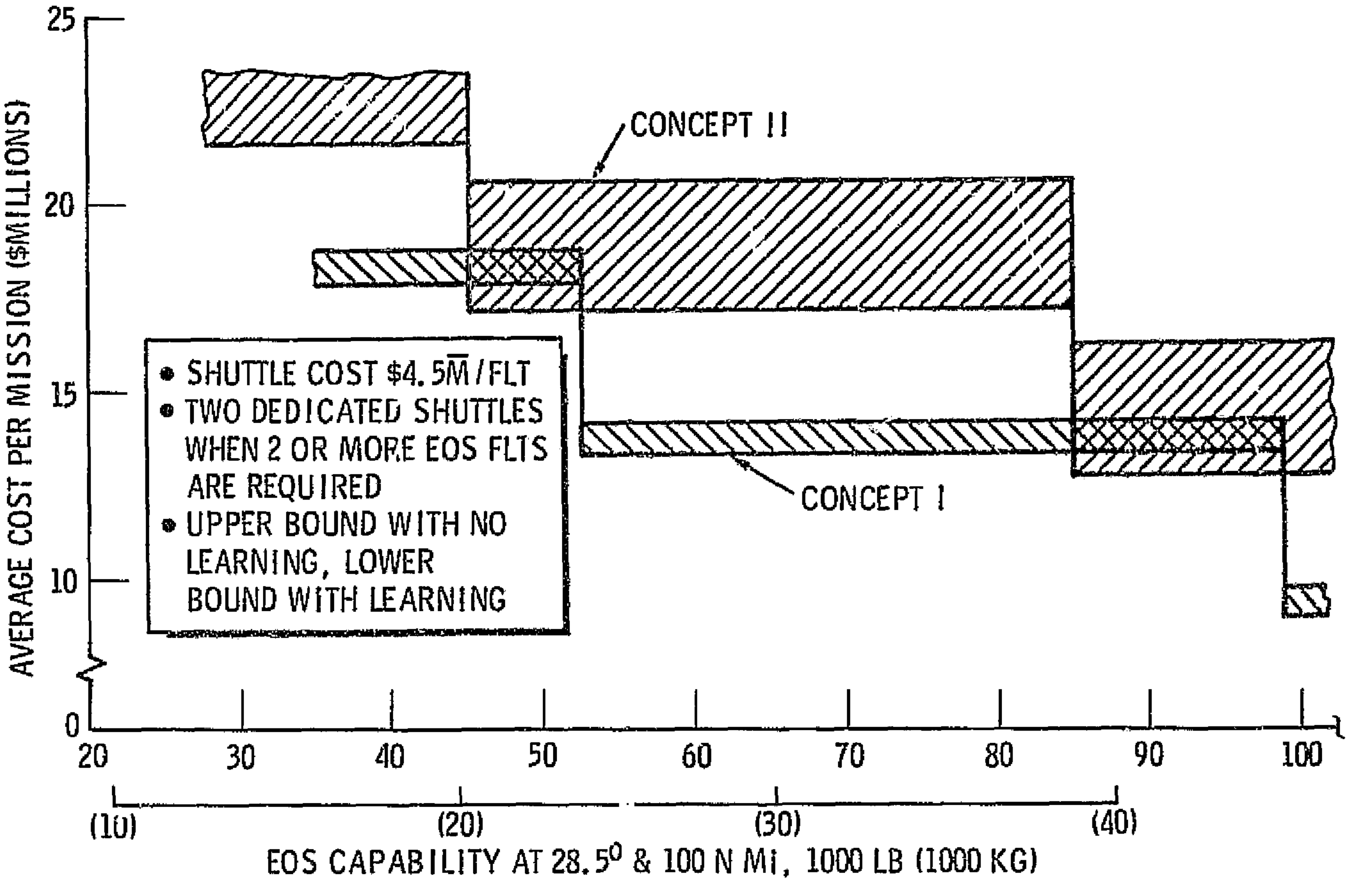


Figure 43. Comparison of Concept Costs for Ground-Based Geosynchronous-Mission Operation

The previous data indicate that for the baseline program (space-based for all missions), all concepts were comparable in total program cost. When a 90-percent learning curve was applied to the recurring hardware costs, concept 11 had a significant improvement in mission costs in those areas where tank set expenditure was required. However, concept 11 was not less expensive than concept 1 in the high-energy earth orbit mission categories. Ground basing of the concepts for the geosynchronous mission indicates that concept 5 had poor economics, because it required an additional shuttle flight due to its excessive length. Concept 1 favors a large shuttle payload to reduce its ground or space-based costs. Concept 11 is less sensitive to shuttle size, but is economically less attractive than concept 1.

Growth Potential and Versatility

The same area of growth potential and versatility discussed in the Phase I evaluation was considered during Phase II, and the data were modified based on new performance data for the three selected concepts. Results of these studies are summarized in Table 11 and 12 for the categories "payload within mission categories" and "alternate mission capability" previously discussed. The results are similar to those already presented in the Phase I evaluation. They indicate that concept 1 has the best growth potential and versatility.

Table 11. Growth Potential and Versatility Payload Within Mission Categories 1000 lb (1000 Kg)

CONCEPT	LOW EARTH ORBIT	OUTBOUND GEOSYNCH		LUNAR LANDING		SUN**** SYNCH	PLANETARY			
							INNER		OUTER	
		1-STAGE (REC)	2-STAGE (REC)	TO SURFACE (UN-MANNED)	ROUND TRIP (MANNED)		1-STAGE (REC)	2-STAGE (REC)	1-STAGE (EXP)	2-STAGE (2ND EXP)
1		10 (4.5)	49 (22)	74 (34)	30 (14)	3.8 (1.7)	11 (5.0)	51 (23)	7.1 (3.2)	21 (9.5)
5		-	10 (4.5)	80** (36)	32.6** (15)	5.6 (2.5)	-	11 (5.0)	0.1 (0.05)	6.7 (3.0)
11		10* (4.5)	28	54*** (24)	22*** (10)	8.8 (4.0) PM ONLY	11* (5.0)	30 (14)	3.2 (1.5)	13 (5.9)
COMMENTS	NOT SIGNIF	CONCEPT 1 HAS CONSIDERABLE GROWTH CAP.		CONCEPTS 1 & 5 HAVE GROWTH CAP.			• CONCEPT 1 ALLOWS SIMPLE SINGLE STAGE OPERATIONS FOR PLANETARY • OTHER CONCEPTS HAVE ADEQUATE CAPABILITY IN 2-STAGE MODES			

*TANK SET EXPENDED
**STAGE & TANK SET
***SMALL STAGE & TANK SET
****GROUND-BASED & CONSTRAINED TO 19,000 LB (8,600 KG) EOS PAYLOAD CAPABILITY

Table 12. Growth Potential and Versatility Alternate Mission Capability

CONCEPT	TRANSLUNAR PAYLOAD 1000 LB (1000 KG)		MAX RESCUE ΔV 1000 FT/SEC (1000 M/SEC)		GEOSYNCH P. L. 1000 LB (1000 KG)	
	ONE-STAGE (EXPENDED)	TWO-STAGE (RECOVERED)	EARTH ORBIT	LUNAR ORBIT	ROUND TRIP (TWO-STAGE)	RETURN TWO-STAGE)
1	37 (17)	51 (23)	23.1 (7.0)	18.2 (5.5)	13 (5.9)	18 (8.2)
5	16 (7.2)	11 (5.0)	17.0 (5.2)	19.6 (6.0)	2.7 (1.2)	3.6 (1.6)
11	27 (12)	30 (14)	20.2 (6.2)	16.7 (5.1)	7.5 (3.4)	10.0 (4.5)
COMMENTS	• ONLY CONCEPT 1 HAS POTENTIALLY ADEQUATE CAPABILITY		• CONCEPT 1 & 11 MARGINAL FOR WORST LUNAR CASE		• CONCEPT 1 CAN CARRY CREW MODULE ROUND TRIP • CONCEPT 1 CAN EMPLACE & RETRIEVE 10 K-LB (4,540 KG) PAYLOAD	

Operations Complexity

Updated information in this evaluation category is presented in Table 13. These data indicate a result similar to that obtained during the Phase I evaluation. Concept 1 always has the fewest number of modules involved in conducting the missions. Concept 5, because of the two-stage geosynchronous operation and the need for a tank set for lunar mission accomplishment, has the largest number of modules in these mission areas.

Table 13. Operations Complexity

CONCEPT	NO. OF MAJOR MODULES			SPACE OPERATION COMPLEXITY* (NUMBER OF DOCKINGS)				NUMBER OF EOS LAUNCHES*			
				GEOSYNCH					GEOSYNCH		
	LOW EARTH ORBIT	GEO-SYNCH	LUNAR LANDING	GRD** BASED	SPACE BASED (NO PF)	SPACE BASED (PF)	LUNAR LANDING (EO ASSY)	LOW EARTH ORBIT	GRD*** BASED	SPACE*** BASED	LUNAR LANDING (EO ASSY)
1	3	2	6	3-4	5	3	3 (M)	1	3	2.3	2
5	3	4	7	5	7	5	4	1	4	2.4	2
11	3	3	7	2	3	3	3 (M)	1	2	1.9	2
COMMENTS	• CONCEPT 1 BEST			• CONCEPT 1 & 11 BEST				• CONCEPT 11 BEST			

* EOS CAPABILITY IS 45,000 LB (20,400 KG) TO 100 N MI (185 KM) & 28.5°
** 2 DEDICATED EARTH ORBITAL SHUTTLES
*** ASSUMES 2 SPACE TUGS ON ORBIT IF NO PROPELLANT FACILITY EXISTS

In the space operations category, concept 11 is the least complex, and concept 5 exhibits considerable complexity. A similar trend appears when the number of shuttle launches are considered, assuming that the EOS has the capability to place 45,000 pounds (20,400 kg) at 28.5 degrees and 100 n mi (185 km).

Based on these data, it is concluded that concept 5 has by far the most complex operational characteristics. Concept 11, because of its low gross weight, requires the least shuttle launches to accomplish the missions. Concept 1, however, has the capability of accomplishing all missions utilizing the same propulsion module staging relationship (single-stage) and conceptually is the simplest.

Risk

Table 14 summarizes the effect of inert weight growth on mission cost and on the ability of the concepts to fit into the EOS bay. Based on the sensitivity data, concept 11 was found to be the least sensitive to inert weight growth, and concept 5 was found to have a greater sensitivity to weight growth than does concept 1. This can be attributed to the two-stage geosynchronous operation for concept 5. In this case, the inert weight growth in both stages of concept 5 exceeded the single-stage, concept 1, growth.

For this reason, concept 5 would have a greater cost risk for the geosynchronous mission. For the lunar landing mission, both concepts 5 and 11 utilize tank sets; whereas, concept 1 retains the same configuration used in the geosynchronous mission. Because of the additional complexity associated with a tank set configuration, it is believed that weight growth for concepts 5 and 11 is more likely than it is for concept 1.

Both concepts 1 and 11 fit into the EOS bay in their geosynchronous and lunar landing configuration. It is assumed that the crew module is integrated on the ground with the intelligence and propulsion modules for the lunar mission. Concept 5 does not fit into the bay for either the geosynchronous or lunar missions. For the geosynchronous mission, the two stages would have to be carried to orbit in two separate shuttle launches. For the lunar landing mission, either the crew module or a stage and tank set would have to be mated on orbit.

Table 14. Effect of Inert Weight Growth on Mission Cost

CONCEPT	WEIGHT GROWTH (+1000 LB/STAGE)				
	COST PER MISSION			FIT EOS BAY?	
	LOW EO	GEOSYNCH	LUNAR LANDING	GEOSYNCH	LUNAR LANDING
1	NOT SIGNIFICANT	$1.0 $\bar{M}$ +7500 LB (3400 KG) PROPELLANT	$1.0 $\bar{M}$ +1600 LB (725 KG) PROPELLANT	YES 49 FT (14.9 $\bar{M}$)	YES 57 FT (17.4 $\bar{M}$)
5		$1.2 $\bar{M}$ +8800 LB (4000 KG) PROPELLANT	GREATER RISK BECAUSE OF TANK SET	NO 66 FT (20.1 $\bar{M}$)	NO 68 FT (20.8 $\bar{M}$)
11		$0.9 $\bar{M}$ +6800 LB (3000 KG) PROPELLANT	GREATER RISK BECAUSE OF TANK SET	YES 51 FT (15.5 $\bar{M}$)	YES 59 FT (18.0 $\bar{M}$)
COMMENTS		• CONCEPT 5 HAS GREATER RISK FOR BOTH CATEGORIES • CONCEPTS 5 & 11 HAVE GREATER RISK FOR LUNAR LANDING MISSION		• CONCEPT 5 TOO LARGE	

SPACE TUG EVOLUTION

All of the previous data has been based on a set of baseline mission model, space tug design, and earth orbital shuttle characteristics. The effect on the space tug of varying some of the basic assumptions is described in this section. Some of the more important considerations are: (1) basing concept, (2) mission model impacts, (3) effects of autonomy and technology (specifically on space tug avionics), and (4) the effects of earth orbital shuttle characteristics.

In the following sections, these considerations are discussed, and potentially attractive space tug evolutionary routes are described.

Basing Concept Implications

An investigation of mission models indicates that space tug missions originating from low earth orbit tend to group into two major initial inclinations: (1) 28.5 to 33 degrees for geosynchronous, planetary, and earth orbit-to-lunar orbit logistics and (2) 55 degrees for space station support missions. A small percent of the missions fall into an odd-orbit category,

and many of these are near-polar inclination missions. Many near-polar inclination missions are low earth orbit and may be accomplished by the EOS alone.

In accomplishing many of the OSSA and DOD missions (planetary and geosynchronous), the space tug originates its mission from 28.5 degrees and may be either space-based or ground-based. The odd-orbit missions generally would require large plane changes to be made for mission initiation from either 28.5-degrees or 55-degrees inclinations, and these missions are best accomplished in a ground-based mode to allow coplanar space operations.

Because of the routine nature of the space station service missions (payload transfer, experiment servicing and placement, and assembly operations), the space tug should be space-based.

Because of the remote location of lunar landing missions, the space tug must be space-based to accomplish these missions. Because of the routine nature of low earth orbit missions in support of lunar missions (translunar shuttle station-keeping, propellant transfer, crew transfer, and cargo transfer), it also is necessary for the service tug in low earth orbit to be space-based.

Ground or space basing of the tug has several implications on the tug itself, on the shuttle, and on other systems. The baseline space tug design is constrained to be space-based. The result of space basing is to require a high degree of reliability/redundancy to assure that routine operations are conducted without the need for refurbishment or servicing other than the replenishment of propellants. Additionally, space basing implies a greater degree of autonomy to allow routine and relatively complex operations with minimum command inputs to the tug. These requirements lead to high avionic component weights, which compromise a large percent of the total space tug inert weight and an even larger percent of the space tug unit cost. Use of a space-based mode does, however, decrease the space tug dependence on earth orbital shuttle size as compared to ground basing. Economics appear to be very dependent upon EOS size whether or not ground space basing is utilized. If the EOS is used directly as a refueling tanker, it must have the capability for routine propellant transfer operations. Alternatively, space basing may require an orbiting propellant facility.

Ground basing relatively decreases reliability/redundancy requirements and the desired degree of autonomy. These reductions are made possible by routine servicing after each mission on the ground and the relative ease of preparing the system sequencing and data for the next mission on the ground. Because the tug must be carried up in the shuttle, preferably fully fueled and with the payload integrated, the gross weight and length of the tug must be

compatible with shuttle capabilities. Otherwise, complex on-orbit operations involving fueling, payload integration, and multiple shuttle flights would be involved. Ground basing for the OSSA and DOD missions leads to a large shuttle payload capability requirement and full utilization of the current cargo bay (15-foot diameter by 60-foot length (4.6-m diameter by 18.3-m length)). Larger bay dimensions would be desired from a tug viewpoint. Ground basing would require electrical, mechanical, and fluid interfaces with the shuttle. Minimum electrical connections would provide assessment to the shuttle of the tug status. Mechanical connections would be necessary for attachment in the bay and to the payload handling equipment. Fluid interfaces would require a closely integrated shuttle and tug development. Even though the space tug may be ground-based for some missions, the ability to achieve space basing when necessary does not appear to be prohibited. Data related to the tug impacts of basing are presented in subsequent sections.

Mission Model Implications

Previous data have been presented on the basis of certain space tug mission assumptions. One of the key groundrules in the sizing of the space tug is the requirement to insert up to 10,000 pounds (4540 kg) to geosynchronous equatorial orbit. Because this payload requirement sized all of the concepts, the effect of this groundrule of space tug characteristics is of interest. Furthermore, a large percent of the space tug missions was in support of the space station and lunar programs. The impact on the tug of eliminating one or the other of these requirements also would be of interest.

Figure 44 illustrates the distribution of the number of payloads as a function of payload weight for DOD and NASA geosynchronous missions. These data indicate that most payloads are considerably less than the design constraint of 10,000 pounds (4540 kg). A design based on 7000 pounds (3180 kg) would be capable of emplacing about 95 percent of the payloads. A 5000-pound (2,270-kg) design could emplace about 92 percent of the payloads, and a 3000-pound (1360-kg) design could emplace about 85 percent of the payloads. This suggests the possibility of designing the space tug for reusable injection of payloads less than 10,000 pound (4540 kg) and the occasional expenditure of the tug for injection of large payloads.

Figure 45 shows the effect on gross weight (space tug inert weight plus propellant weight plus payload weight) of varying the inert and payload weight for the geosynchronous equatorial insertion mission. The baseline for concept 1 is shown as a zero inert weight change at 10,000 pounds (4540 kg) of payload [99,000 pounds (or 45,000 kg) gross weight]. The effect of reducing payload is to reduce gross weight by a ratio of 3.5 lb/lb of payload weight. At the 5000-pound (2270-kg) payload suggested by the payload distribution data, the gross weight is reduced to about 82,000 pounds (37,200 kg).

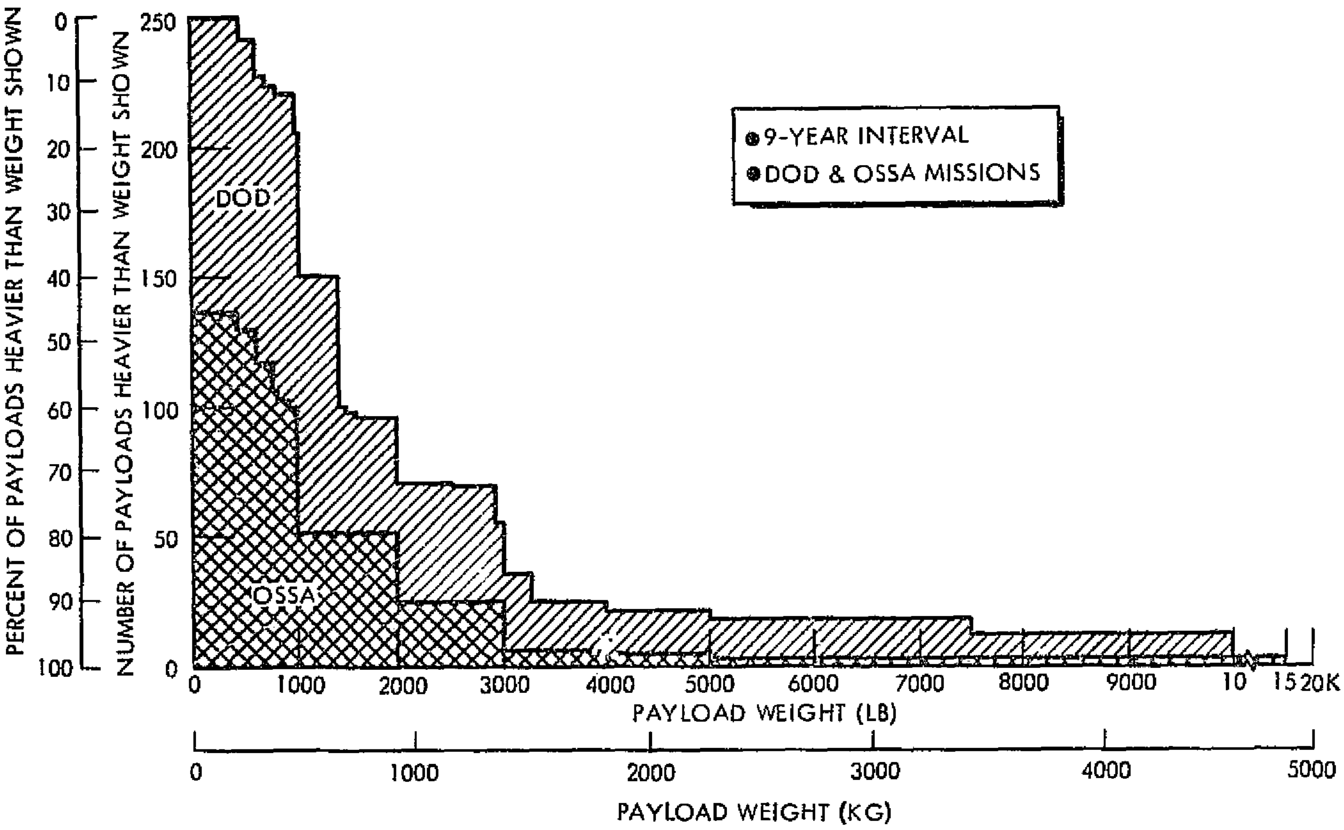


Figure 44. Geosynchronous Payload Weight Distribution

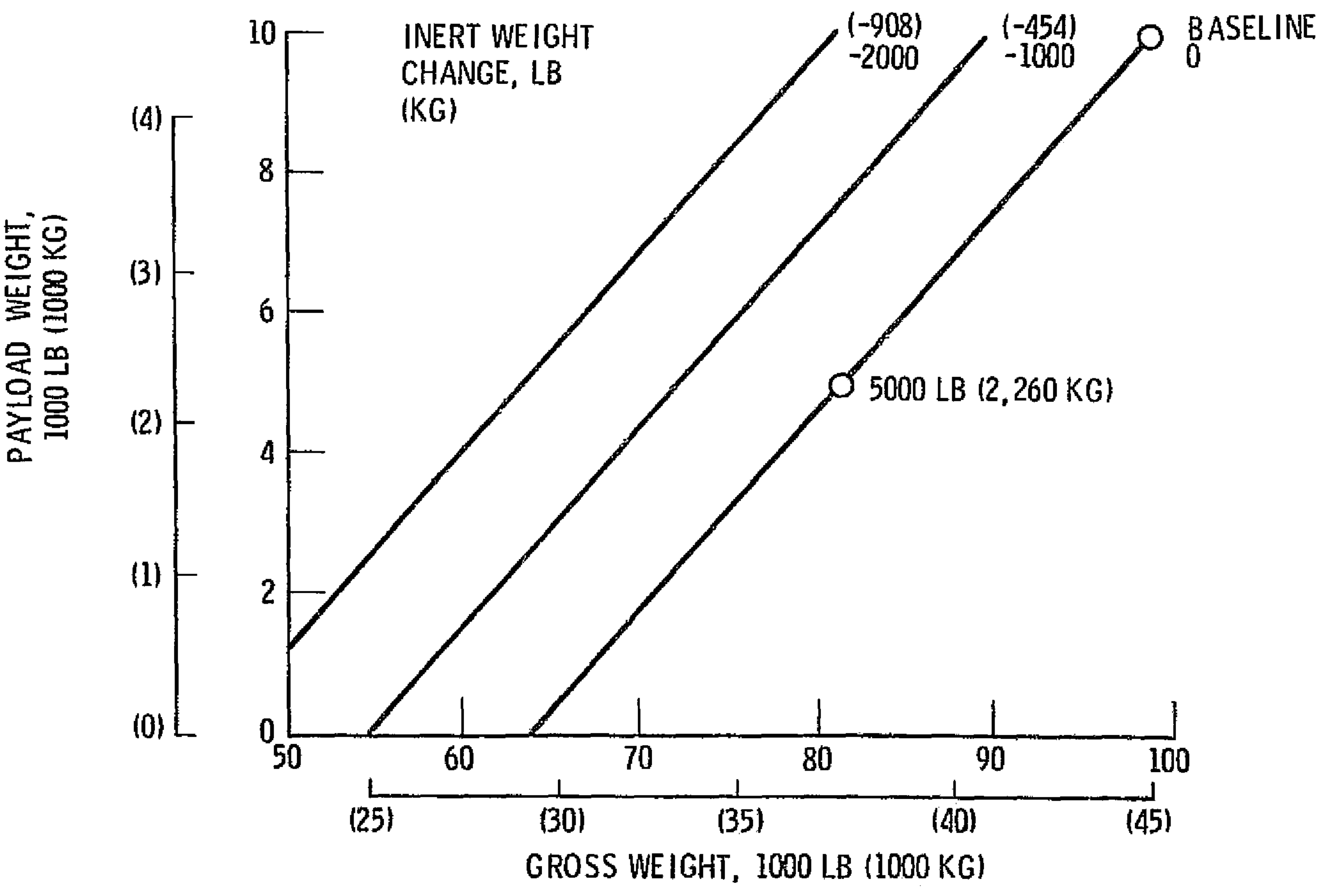


Figure 45. Effect of Payload Weight on Gross Weight for Recoverable Single-Stage Geosynchronous Mission

Reductions in payload capability are not achieved without potential operational penalties. One of the penalties involved is a reduction in payload capability when multiple payloads are inserted at geosynchronous conditions. Because many of the payloads are of low weight, the possibility of clustering payloads to further achieve economic operations has been considered. The 43 missions in this category already have assumed this capability.

Figure 46 shows the effect of phasing time on the maximum payload capability for concept 1 when two equally sized payloads are inserted 180 degrees apart in geosynchronous equatorial orbit. Two curves are shown: one depicting the capability for the baseline concept designed to carry a single 10,000-pound (4540-kg) payload to geosynchronous orbit, and the other showing the capability for a stage designed for a single 5000-pound (2260-kg) payload insertion. When both boiloff and main propulsion propellant requirements are considered, the maximum payload capability occurs at about 260 hours of phasing time. However, because the EOS cannot stay on orbit (assuming a ground-based operation) for this period of time, phasing time must be restricted to less than 100 hours, which is near the knee in the curve. These data indicate that the maximum total payload capability is 6700 pounds (3040 kg) for the 10,000-pound (4540-kg) design and 1700 pounds (770 kg) for the 5000-pound (2260-kg) design. Under these circumstances, it is doubtful that a design constrained to a 5000-pound (2260-kg) payload would have the capability for multiple payload deployment. This implies that the number of missions would increase to about 140 rather than to 43.

Another consideration is the ability to retrieve malfunctioning payloads at geosynchronous conditions. A 10,000 pound (4540 kg) design can retrieve 3900 pounds (1,760 kg); whereas, a 5000 pound (2260 kg) design can only retrieve 1900 pounds (860 kg). Additional study of the consequences of payload reduction from 10,000 pounds (4540 kg) is required to establish the impact on operational efficiency.

In the event that a space station program does not exist in the time period originally anticipated in the baseline model, the inherent capability of the space tug to provide manned operations on orbit for periods of time up to 28 days (4 men) would allow manned operations in space for extended periods. Even if a space station did exist, the ability to carry the space tug to any orbit in the EOS allows manned operations for long periods in orbits other than the space station orbit. Such a concept is shown in Figure 47. The crew module when attached to the intelligence module allows manned operations. If the space tug fuel cells are employed for power, it would be necessary to attach a small skirt module containing hydrogen and oxygen expendables. The amount of expendables could be reduced by adding solar cells to the space tug to provide power. The crew module shell also could

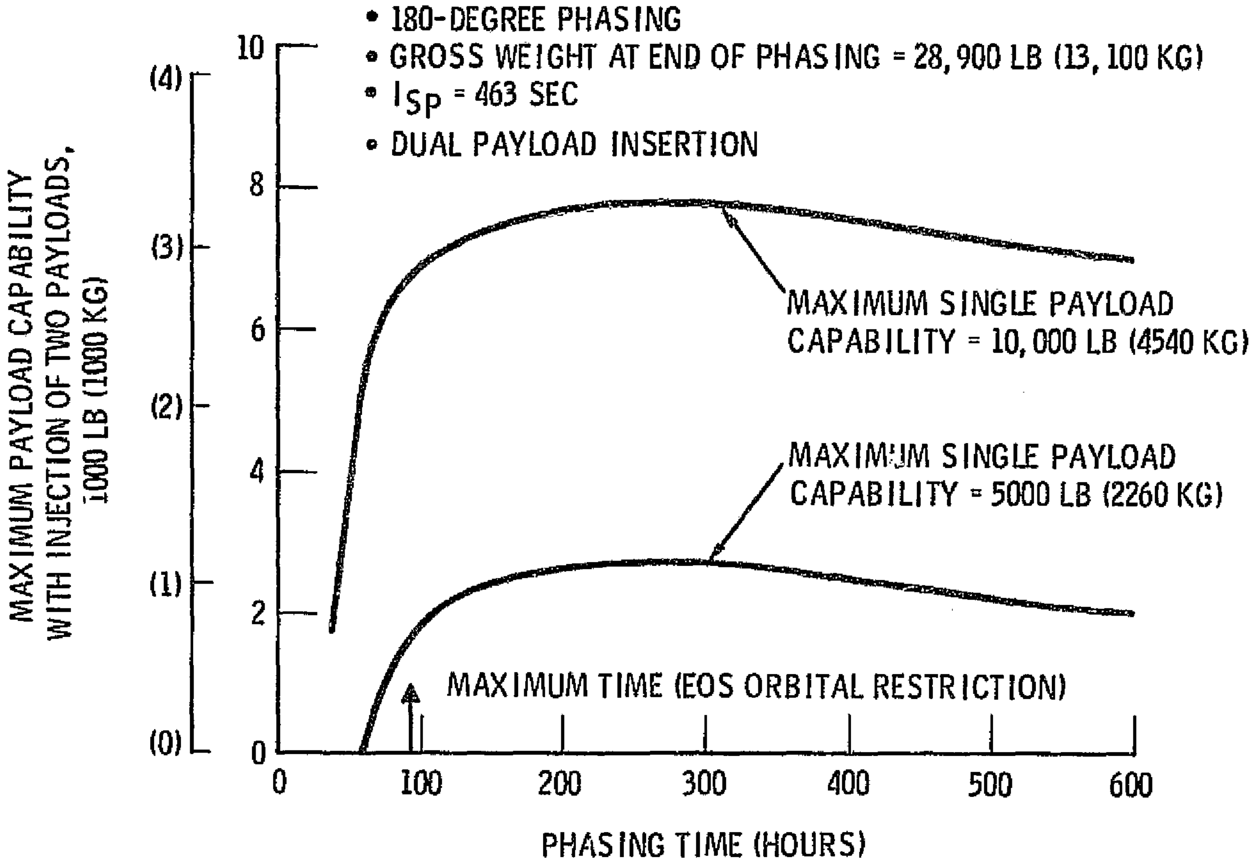


Figure 46. Effect of Phasing Time on Maximum Payload Capability

TUG CAPABILITIES

- 6 MEN/CREW MODULE
- COMPLETE ASTRIONICS
- ~ 45-DAY RESUPPLY PERIODS
- SOLAR CELL OR SOLAR CELL/CMG KIT
- ANY ORBIT EOS LAUNCH

Figure 47. Space Tug as Interim Space Station

double as a container for experiments that would accompany the manned mission. Retrieval or resupply of this mini-station would be accomplished by the EOS.

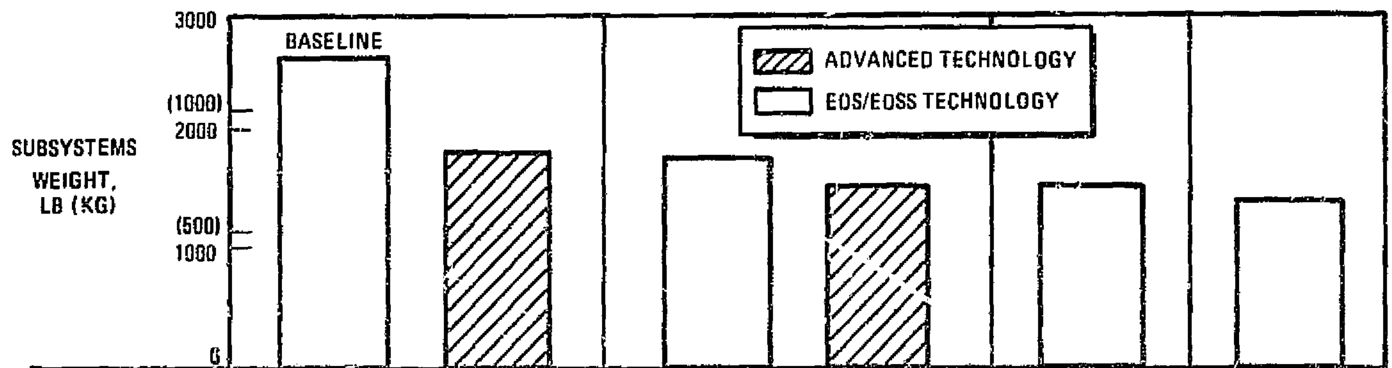
In the event that the lunar program were no longer considered as a required design condition for the space tug, no change to the basic approach would occur since the primary driver mission was the geosynchronous mission. In approaching the lunar mission tug design, a rather significant block change to the basic design is anticipated to make it compatible with the required landing and crew functions. From an overall mission model viewpoint, even if the lunar missions are not included, the space tug fulfills a significant function in earth orbit by injecting and retrieving payloads and providing support to low earth orbit missions near the space station.

Effect of Autonomy and Basing on Subsystems

The baseline system, previously described was designed to be space-based with maximum autonomy and utilized shuttle and space station technology. Because of the potential interest in ground basing for many of the space tug missions, the effect of the resulting changes on subsystems requirements and weights is of interest. Additionally, the influence of various degrees of autonomy on subsystems weight and the potential weight reductions that may be possible by utilizing advanced technology subsystems is also of interest. Since these subsystems comprise a large percentage of the space tug inert weight, it may be anticipated that weight reductions in this area would have a significant impact on tug size, weight, and cost.

Figure 48 illustrates the effect of these factors on subsystems weights, propellant requirements, gross weight, unit cost, and cost/mission for the geosynchronous mission. The differences in capability implied by maximum, medium, and minimum autonomy are as follows: (1) maximum autonomy implies the capability to rendezvous and dock automatically, the ability to initiate a mission by communicating only the target ephemeris and the ability to conduct a self checkout; (2) medium autonomy implies the same capability as maximum autonomy, except that automatic rendezvous and docking sensors and associated memory are removed (control in this phase by another external system is necessary); (3) minimum autonomy implies a less precise navigation capability which degrades injection accuracy and requires ground tracking and communication for mission accomplishment as well as the removal of capability implied by medium autonomy.

- 7-DAY MISSION, FUEL CELL POWER
- UNMANNED EARTH ORBITAL FLIGHT
- G,N, &C COMM & DATA MGT, EPS, THERMAL, ACS, PROP MGMT



BASING	SPACE		GROUND		GROUND	GROUND
AUTONOMY	MAX		MAX		MED	MIN
W_{PROP}*	78 (35.4)	73.1 (34.2)	72.0 (32.7)	70.0 (31.8)	70.1 (31.8)	68.6 (31.2)
W_{GROSS}*	99 (45.0)	91.9 (41.7)	91.8 (41.7)	89.5 (40.6)	89.6 (40.6)	87.8 (39.8)
UNIT COST	50.0 $\bar{M}$	32.6 $\bar{M}$	32.5 $\bar{M}$	26.8 $\bar{M}$	26.8 $\bar{M}$	22.5 $\bar{M}$
COST/MISS**	12.9 $\bar{M}$	11.3 $\bar{M}$	6.1 $\bar{M}$	5.8 $\bar{M}$	5.8 $\bar{M}$	5.6 $\bar{M}$

*1000 LB (1000 KG) **GROUND-BASED ASSUMES 1 SHUTTLE FLIGHT

Figure 48. Effect of Autonomy and Basing on Subsystems Weight

The primary difference between space and ground based subsystems is the reduction in redundancy because of the ability to check out and replace components on the ground between missions. The data shown on this chart indicate that a large decrease in subsystems weight is associated with ground basing. The related large change in unit cost is attributable to the large cost factors applied to avionics subsystems, about \$22,000/pound (\$48,000/kg). The effects on gross weight of basing is also rather large [from 99,000 pounds (45,000 kg) gross weight to 91,800 pounds (41,700 kg)].

Utilization of technology advanced beyond EOS/EOSS technology in the computer hardware and software, guidance and navigation hardware, and communications hardware also leads to large reductions in subsystems weight. A thorough discussion of these changes is given in the subsystems portion of the final report (Volume 5).

First unit costs used as a baseline are considered to be very conservative values. The effect of several variables (first unit cost, number of reuses, basing concept, and EOS size) on the total 10-year geosynchronous mission cost is shown in Figure 49. These data include a refurbishment cost of 3 percent of first unit cost for each mission for ground based operations

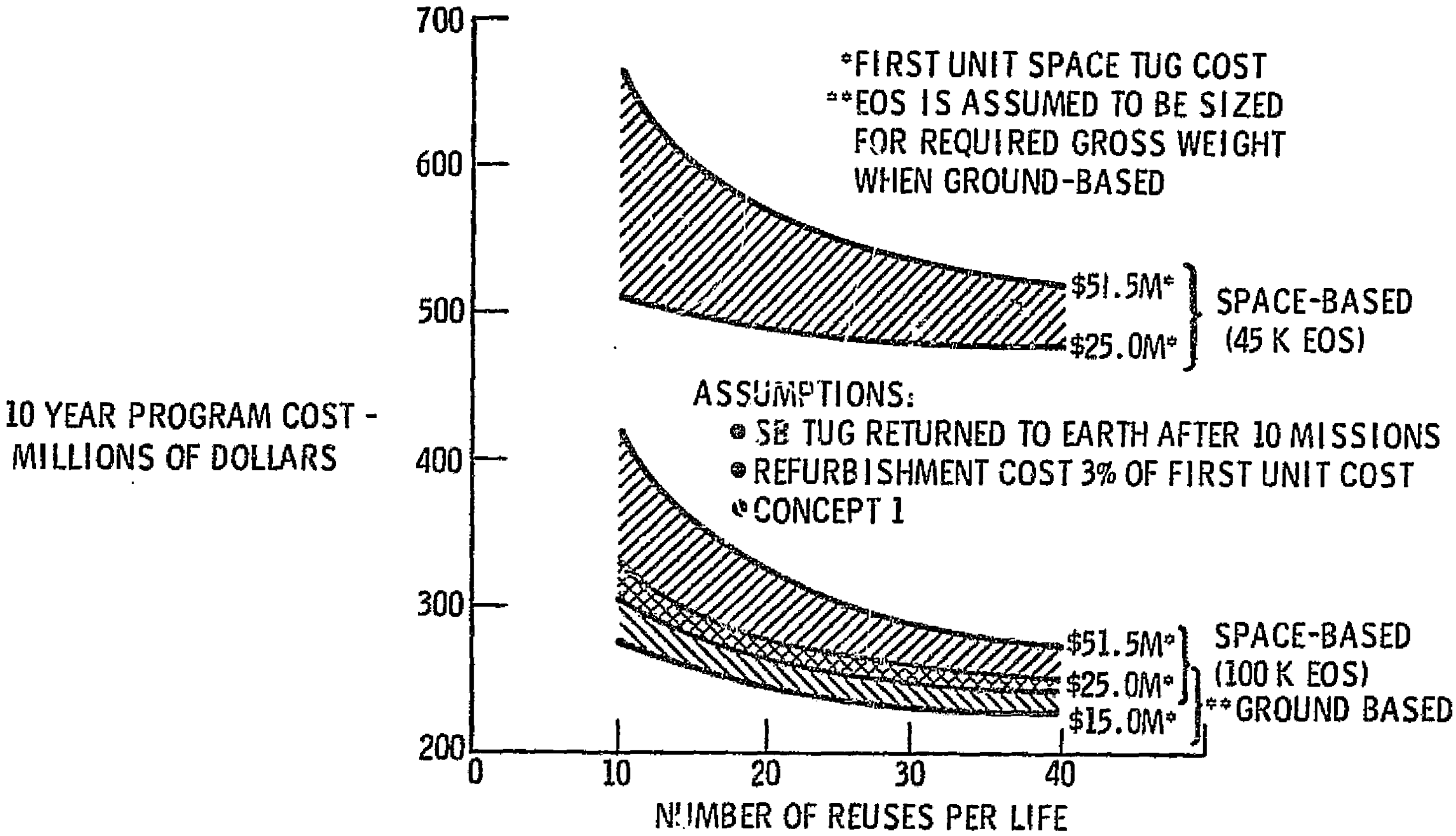


Figure 49. Effect of Variables on Total 10 Year Geosynchronous Mission Cost

and 3 percent of first unit cost for each 10 missions for space-based operations. These data indicate that the total program cost becomes relatively insensitive to unit cost and the number of reuses as the number of reuses approach 25 to 30. The payload capability of the shuttle at 100 nautical miles (185 km) and 28.5 degrees is shown to have a large impact on the program cost.

Effect of EOS Characteristics

Although EOS payload weight capability and bay dimensions are significant concept drivers for the space tug, particularly when ground-based operations are considered, the manner in which cargo is handled and the ability of the shuttle and tug to share the shuttle orbital maneuvering system (OMS) propellants necessary for an abort during ascent are also very significant to the design.

Three of the cargo handling concepts being studied for the EOS are shown in Figure 50. The first scheme requires that the tug be docked at the aft end. This results in multiple engines on the tug or alternatively a very large docking gear around a single engine, both of which lead to large weight penalties. The second scheme implies the need for docking on the side of the tug, but allows for the use of a single engine. The third concept utilizes manipulators to remove and insert cargo into the bay. This concept removes

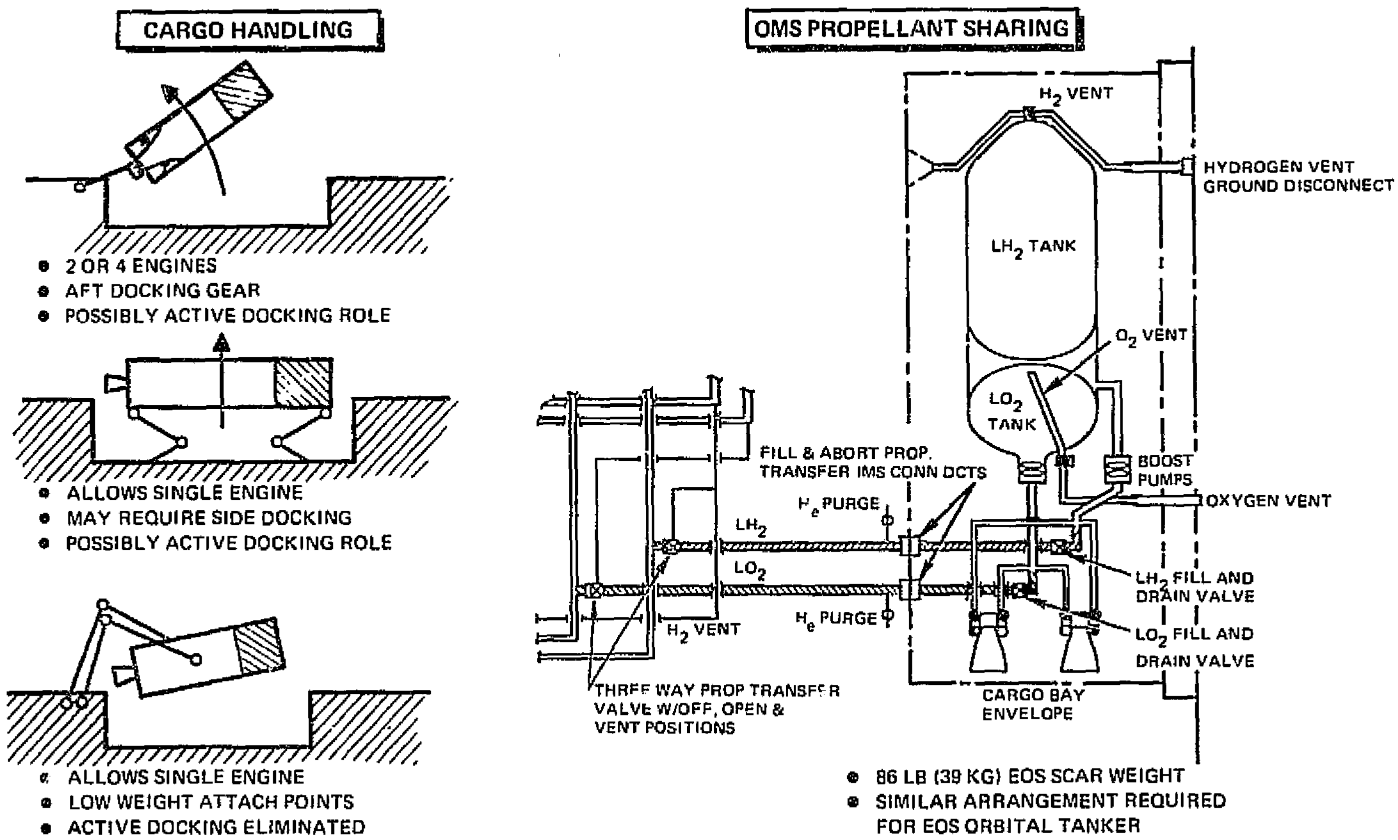


Figure 50. Effect of EOS Characteristics on Tug

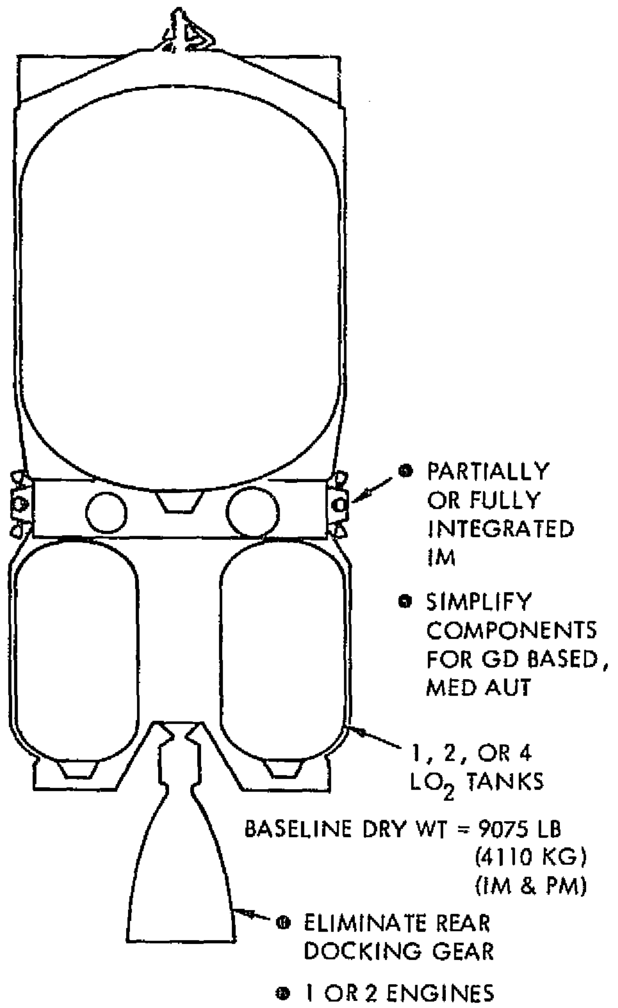
the requirement for active docking by tug entirely (only stabilization is necessary). It also allows use of a single engine. This last approach appears to have significant advantages from a space tug point of view. Under any circumstances, provisions are necessary for fastening the space tug in the bay to react normally under lateral loads induced during launch, reentry, and landing.

During ascent to orbit, the current shuttle design requires up to 25,000 pounds (11,300 kg) of propellant in the OMS to be used in the event of an engine failure in the orbiter stage. During a normal mission, this propellant is available on orbit. Since this system and the tug both use LO_2/LH_2 propellants, the possibility exists of sharing these propellants with the tug to increase the payload capability of the shuttle by 25,000 pounds (11,300 kg). Two schemes may be used to allow this sharing. One of these would require the shuttle to pump the propellants into an off-loaded tug when on orbit. In the other scheme, the tug is fully loaded with propellants and the OMS propellants are obtained from the tug only in the event of an abort. A schematic of interconnecting plumbing is shown on Figure 50. The resulting EOS scar weight is only 86 pounds (39 kg). This scheme could also apply to the EOS when it conducts routine orbital propellant tanker missions.

As a result of varying from a rear docking requirement (assuming compatible EOS cargo handling), several simplifications of the baseline design are possible. Some of these are indicated on Figure 51 for concept 1. Removal of the rear docking gear and replacement of the 4 engines by 1 leads to a 560 pounds (250 kg) inert weight reduction and a 0.9 foot (0.27 m) length increase if 4 LO_2 tanks are used and a 910 pound (410 kg) weight decrease and 5.2 foot (1.6 m) length increase if a single LO_2 tank is used. Furthermore, total integration of the IM components into the PM reduces weight by 400 pounds (180 kg) and retention of only modular avionics reduces weight by 200 pounds (90 kg). Ground basing with medium autonomy could reduce inert weight by about 1050 pounds (465 kg). Utilization of advanced avionics technology and ground basing reduces inert weight by about 1060 pounds (470 kg).

Certain of these changes to the baseline were combined to establish two simplified concept 1 designs (1' and 1''). Concepts 1' and 1'' have the changes from the baseline indicated by the shaded areas on this chart. The result of these changes is to reduce propellant requirements from 78,000 pounds (35,300 kg) for the baseline design to 63,000 pounds (28,600 kg) for concept 1' and 64,400 pounds (29,100 kg) for Concept 1''. Dry weight is also reduced significantly. The unit recurring cost reduction was also calculated and the major change in unit cost is attributable to a reduction in expensive avionic system components. The unit cost was reduced from about $50 million for the baseline concept to $25 million for Concept 1' and $26 million for Concept 1''. The reduction for concept 1'' assumed that the advanced avionics components have the same cost per unit weight as the EOS/EOSS-type components. Considerable effort would be required to determine a valid cost for the advanced avionics components.

Figure 52 shows the effect of the reduced inert weights for concepts 1' and 1'' on gross weight for the geosynchronous mission, including a 10,000 pounds (4,540 kg) payload. Whereas the baseline single stage recoverable system has a gross weight of 99,000 pounds (44,900 kg), the inert weight changes in concepts 1' and 1'' result in gross weights of 80,000 pounds (36,300 kg) and 82,000 pounds (37,200 kg) respectively. Dependent upon choice of concept approach, the shuttle payload requirement at 28.5 degrees and 100 nautical miles (185 km) could vary between 80,000 and 99,000 pounds (36,300 and 44,900 kg). Utilization of OMS propellant sharing reduces this requirement to between 55,000 and 74,000 pounds (25,000 and 33,600 kg), assuming that 25,000 pounds (11,300 kg) of propellant can be shared.



CHANGE	ΔW, LB (KG)	ΔL, FT (M)
2 ENG, 2 LO_2 TANKS, NO AFT DOCKING	-410 (-190)	+1.2 (0.37)
1 ENG, 4 LO_2 TANKS, NO AFT DOCKING	-560 (-250)	+0.9 (0.27)
1 ENG, 1 LO_2 TANK, NO AFT DOCKING	-910 (-410)	+5.2 (1.6)
TOTALLY INTEG IM COMPONENTS	-400 (-180)	-3.8 (1.2)
MODULAR AVIONICS ONLY	-200 (-90)	-3.4 (1.0)
GRD-BASED, MED AUTONOMY	-1050 (-480)	-2.1 (0.64)
GRD-BASED, MAX AUTONOMY, ADV AVIONICS	-1060 (480)	-2.1 (0.64)

1' DRY WT = 6265 LB (2840 KG), FIRST UNIT ≈ \$25 $\overline{M}$, W_{PROP} = 63,000 LB (28,000 KG)

1" DRY WT = 6605 LB (3000 KG), FIRST UNIT ≈ \$26 $\overline{M}$, W_p = 64,400 LB (29,100 KG)

Figure 51. Potential Simplification of Baseline

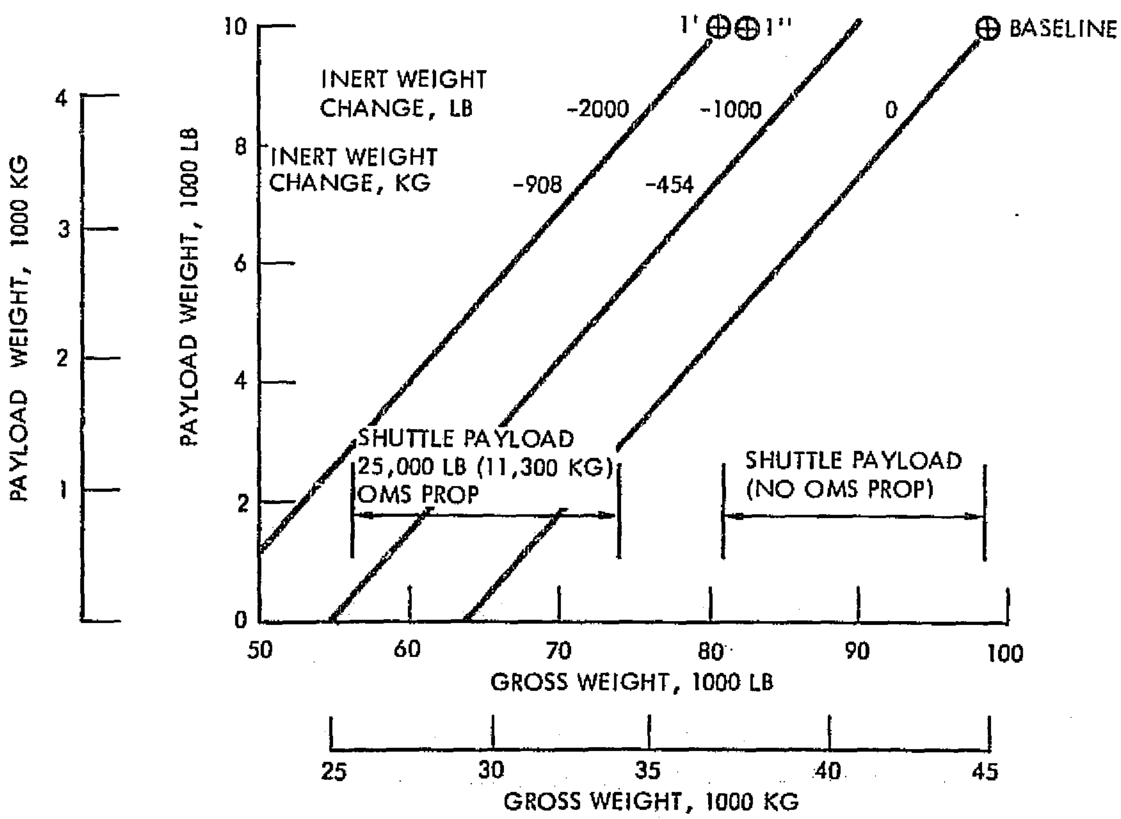


Figure 52. Effect of Inert Weight on Gross Weight for Recoverable Single-Stage Geosynchronous Mission

Potential Evolutionary Approaches

Figure 53 indicates a potential evolutionary approach for the space tug system, indicating the buildup of capabilities ranging from initial operations to the lunar landing mission.

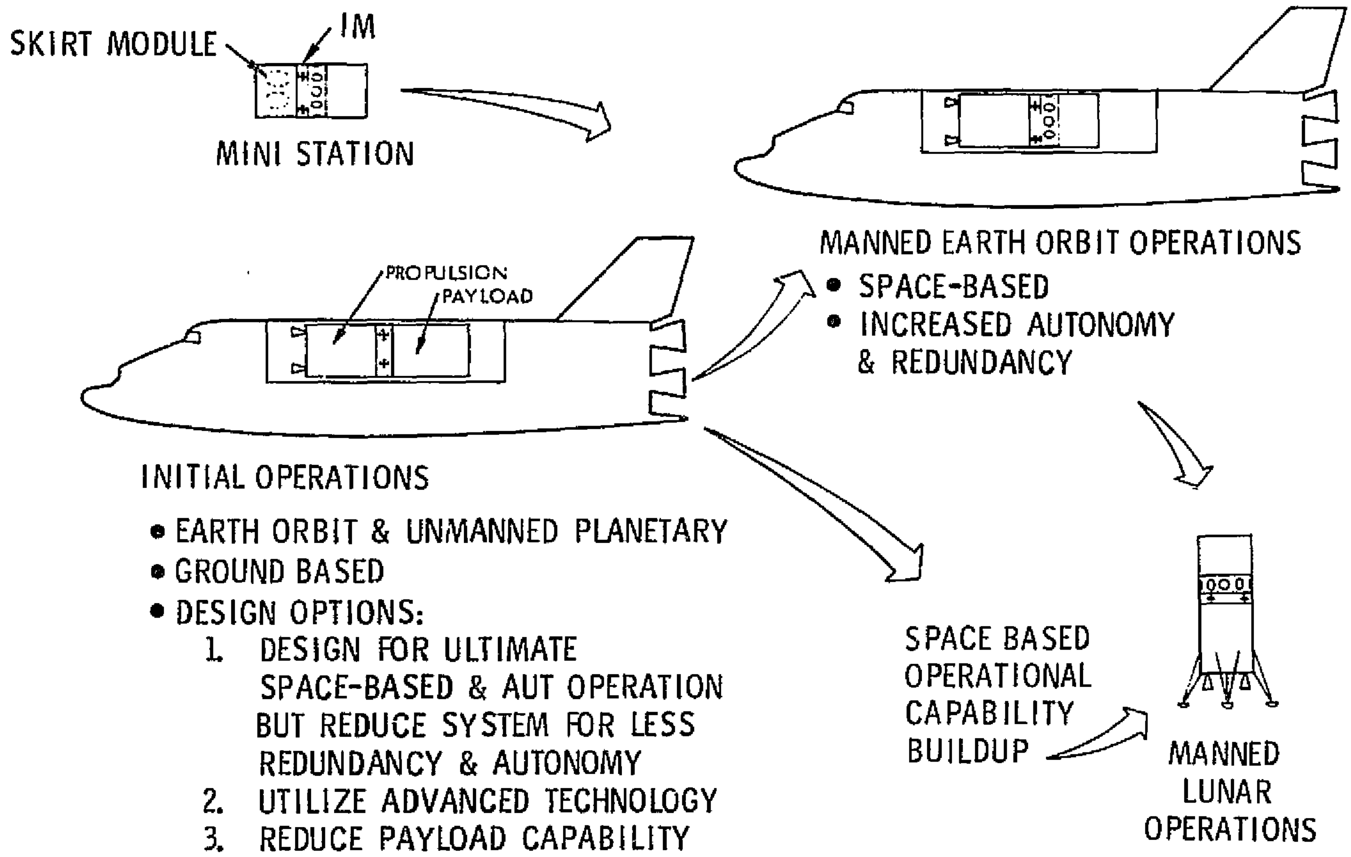


Figure 53. Space Tug Evolution

Initial operations of the propulsion and intelligence modules will probably be ground based and unmanned. The tug will be used to accomplish the missions in earth orbit outside the range of EOS capability and will also be used for planetary injection missions. The crew module may evolve as an earth orbital mini-station described previously. Initially, it may be used in the shuttle bay, but later missions may be conducted in a free-flying configuration.

Together, the crew module, propulsion module, and intelligence module will eventually provide a manned on-orbit capability for assembly, payload transfer, crew transfer, experiment servicing and other support missions. During this period of time, the capability of conducting space-based operations will be attained. These capabilities will then allow manned lunar operations to be conducted. To achieve this final capability, the space tug requires addition of the lunar landing kit and cargo pods and several changes to the propulsion and intelligence modules to allow lunar landing mission capability.

Because of the impact of stage inert weight on gross weight for the high-energy geosynchronous and planetary missions, it is important that the inert weight of the tug be minimized to assure compatibility with the shuttle payload capability when ground based. As shown previously, this may be accomplished in several ways. These include single engine design without rear docking, reduction in avionics components weights by reducing redundancy and autonomy or by utilizing advanced technology, by partial or total integration of the intelligence module components into the propulsion module, and by utilizing OMS propellant sharing. Elimination of rear docking and resulting single engine design is contingent upon shuttle design philosophy. OMS propellant sharing is also heavily dependent upon the shuttle design philosophy. Considerable detailed subsystems design analysis is necessary to determine the practicality of evolving from a comparatively simple ground-based avionics system to a fully autonomous space-based capability without invoking a major design change when space basing is required. To critically determine the benefits and the costs associated with the utilization of advanced avionics technology, research studies specifically aimed at a definition of the design approaches are necessary.

Although partial or total integration of the IM components into the propulsion module reduces inert weight, it also eliminates potentially-attractive uses of a totally modular approach. For example, the mini-station concept requires only the IM and a small skirt module that contains LO_2/LH_2 for power, life support, and attitude control. This small system, when attached to the crew module and experiment modules, could fit into the cargo bay to accomplish manned missions in any orbit. This implies a desire to either have a totally modular IM or, at a minimum, an IM containing at least the avionics. Concepts that allow integrated avionics and tankage in a submodule that may be used for mini-station type missions have been considered and appear to be consistent with the single-stage concept 1. The small propulsion module of Concept 11 (1-1/2 stage) is already compatible with this requirement.

A final approach to reducing the gross weight of the tug in the shuttle for ground-basing operations is to reduce the design payload requirement to less than 10,000 pounds (4,540 kg). As shown, this may inhibit multiple payload injection and payload retrieval operations.

Additional, closely coupled, shuttle and tug design studies are necessary to fully develop the most feasible evolutionary approach and to assure shuttle/tug compatibility. Since advanced avionics may allow a low-weight fully autonomous approach, studies related to these systems are also key to developing the most desirable approach.

Figure 54 summarizes the preliminary space tug development schedule and is consistent with the overall evolutionary approach previously discussed. Following the current study, a Phase A study is anticipated to resolve the primary remaining issues. Following the Phase A study, a Phase B study will be necessary for the unmanned space tug and will detail the design of the propulsion and intelligence modules for that application. This would be followed by development of the unmanned tug. Another Phase C will be conducted to detail the design for manned earth orbital applications. This will result in the detailed design of the crew module and in the design changes necessary in the propulsion and intelligence modules for compatibility. Initiation of development of this capability would lay the unmanned development by about 2 years.

Finally, another Phase B is planned to determine the design approach for the lunar landing tug version. Although the Phase B initially conducted for the overall system considered the lunar mission, it is believed that the changes for the lunar application are severe enough to require another Phase B to be conducted. Phases C and D would follow with an anticipated IOC in 1983.

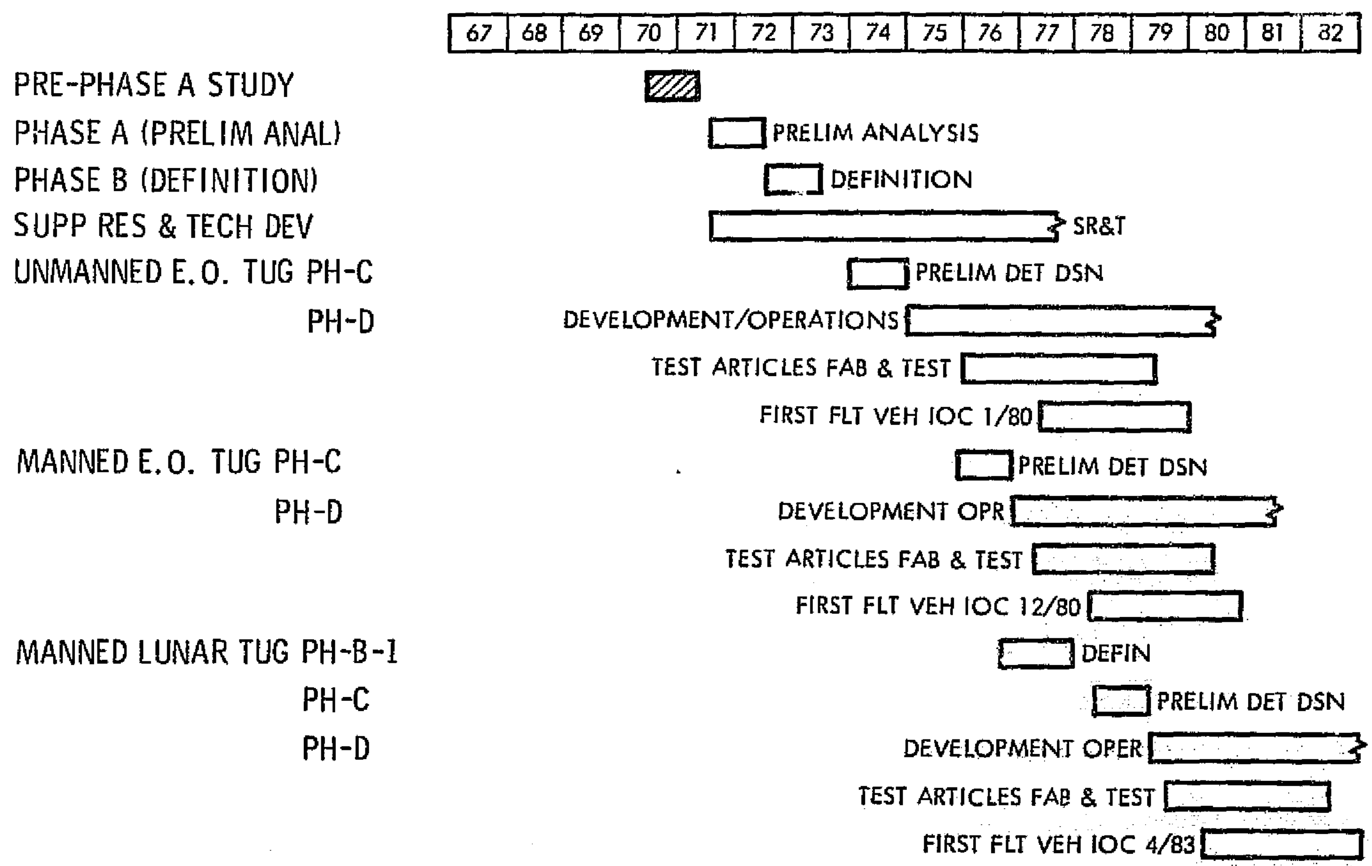
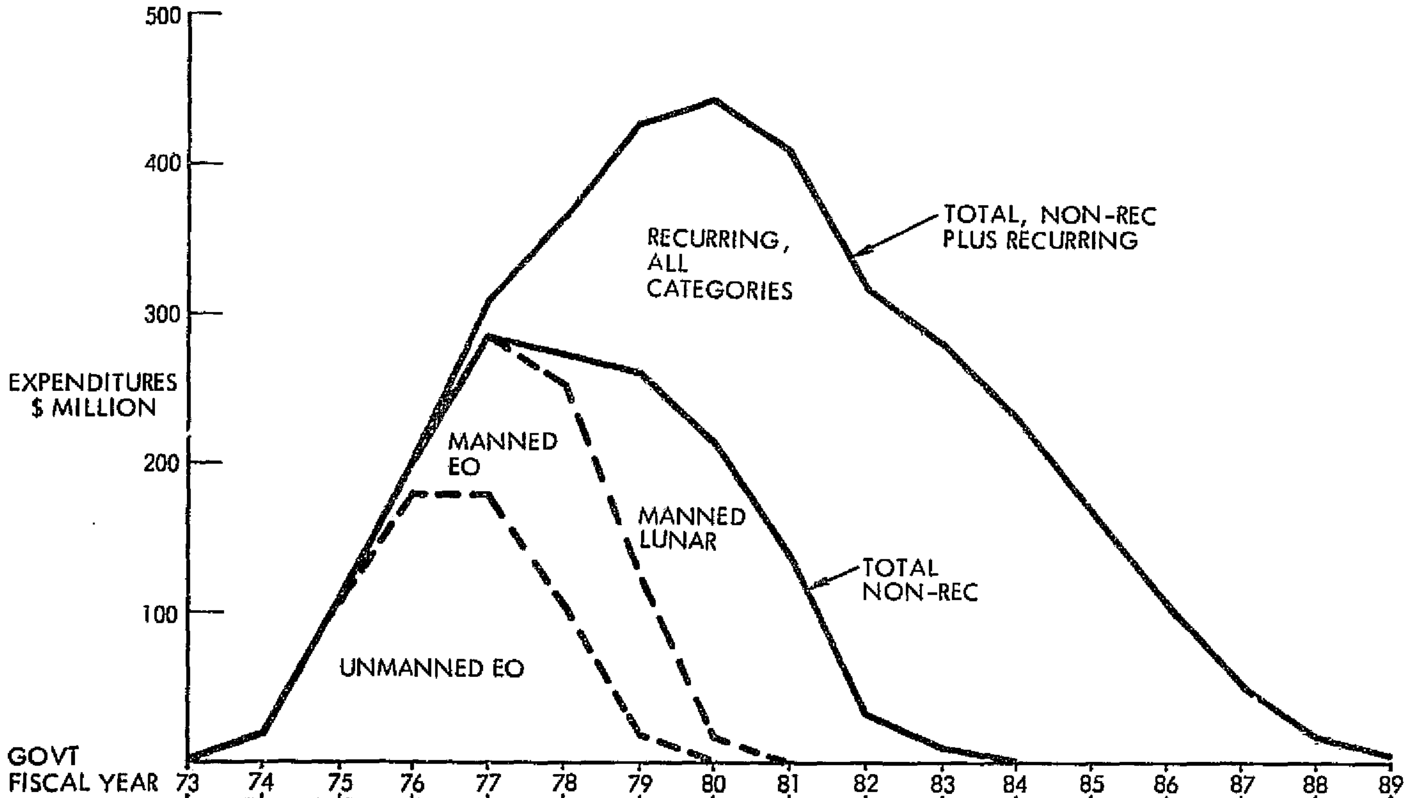


Figure 54. Preliminary Program Development Summary Schedule

Figure 55 summarizes the annual costs for development and production. Development costs are shown for each of the three development categories. Although this chart is specifically for concept 1, the development costs of the other concepts are similar. Peak program costs occur between 1978 and 1980 and are $450 million. Peak development cost occurs in 1978 and is $300 million. Total development cost is $1.47 billion. Of this total, $560 million is for the unmanned earth orbital development, $390 million is for manned earth orbital development, and $520 million is for lunar mission development.



GOVT FISCAL YEAR	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
NON-REC	0	22	108	193	280	274	261	209	133	30	8						
REC	0	0	0	0	38	103	150	180	194	193	178	154	121	84	52	20	3
TOTAL	0	22	108	193	318	377	411	389	327	223	186	154	121	84	52	20	3

Figure 55. Design Concept 1 Annual Funding Requirements

COMPARISON OF SPACE TUG AND OTHER SYSTEMS

Alternate system or operational approaches have been considered in the several mission areas that have been studied for the space tug. In the low earth-orbit space station support area, the alternatives for payload delivery have included direct EOS delivery to the space station and transfer of payloads between a low earth orbit and the space station by the tug. Additionally, consideration has been given to self-propelled experiment modules near the space station rather than deployment and retrieval by the space tug.

In the lunar mission area, no systems have been considered as competitive with the space tug for lunar landing. During this study, however,

consideration has been given to the use of the tug in conjunction with the translunar shuttle (chemical or nuclear) to improve payload delivery efficiency.

In the geosynchronous and unmanned planetary mission area, the use of LO_2/LH_2 and storable (e.g., N_2O4/A-50) expendable stages have been considered as an alternate solution. In the following discussion, comparisons will be made in each of the mission areas between the space tug and competing system or operational approaches.

Space Station Support

The largest portion of space tug missions were identified in support of the space station. These included (1) transfer of payloads between the space station at 270 nautical miles (500 km) and the shuttle on orbit at 100 nautical miles (185 km); (2) placement, retrieval, and servicing of experiment modules near the space station; and (3) other categories of missions including space station assembly and near space station abort and rescue.

Several mission concepts have been considered for transferring payload, including transfer over small distances (hundreds of yards) and transfer over relatively large distances [e.g., between 100 nautical miles (185 km) and 270 nautical miles (500 km) orbits].

Transfer of payloads by the tug over large distances was considered to determine whether this mode would significantly increase the net payload deliverable by the shuttle. Figure 56 shows the effect of several space tug parameters on an efficiency coefficient defined as the ratio of payload delivered round trip to the propellant consumed in achieving the delivery. For this case, a payload of 40,000 pounds (18,100 kg) is assumed to be delivered round trip between 100 and 270 nautical miles (185 and 500 km). This data shows the effect of propulsion module size, the effect of unmanned delivery, and the effect of manned delivery for a large and small crew module. Both fully loaded propulsion modules and propulsion modules off-loaded for one round trip are shown.

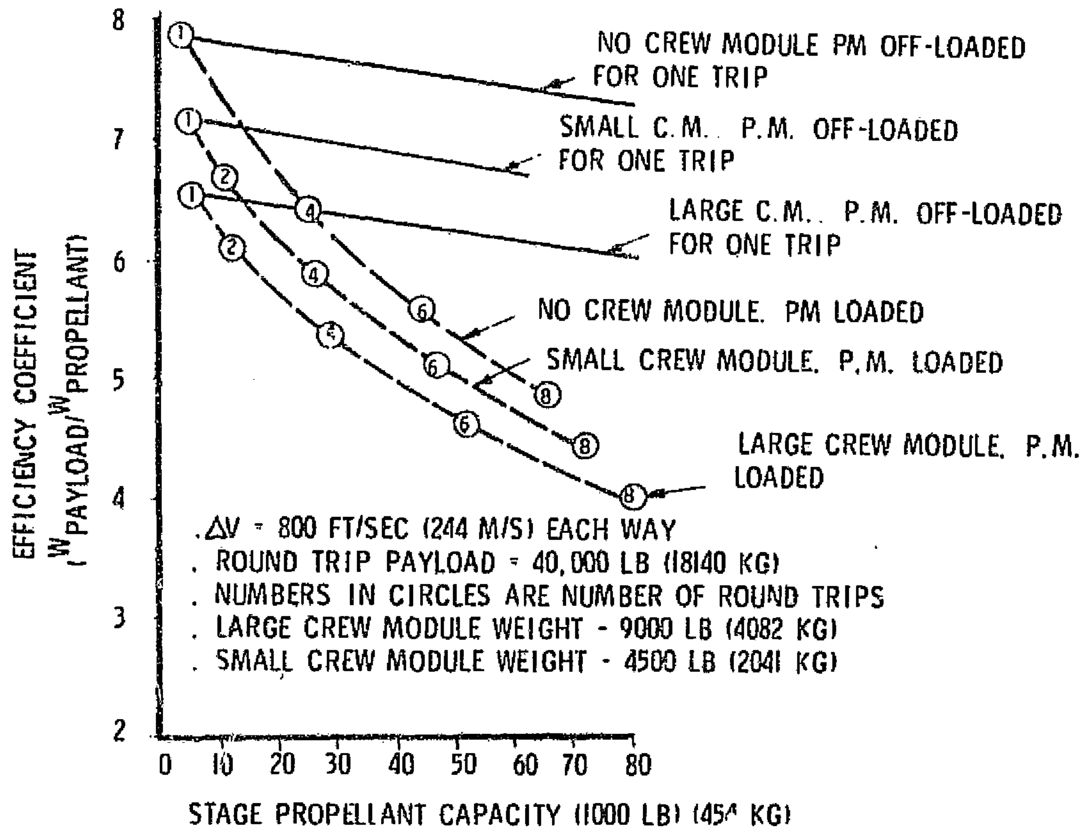


Figure 56. Payload Efficiency

These data indicate that fully loaded large propulsion modules can make many round trips, but the efficiency coefficient drops off rapidly with stage propellant capacity. Offloading the propulsion module for a single trip does not significantly reduce the efficiency coefficient at large propulsion module sizes. The effect of going from unmanned transfer (no crew module) to a large lunar shelter size crew module reduces the payload efficiency coefficient by about 16 percent.

Figure 57 shows the net payload (actual payload less space tug propellants) delivered between 100 and 270 nautical miles (185 and 500 km), assuming a round trip delivery. The shuttle payload at 100 nautical miles (185 km) is assumed to be 37,000 pounds (16,800 kg). If the shuttle had delivered the payload to 270 nautical miles (500 km), it would have been able to deliver 25,000 pounds (11,300 kg). These data indicate that the space tug must have an efficiency coefficient of greater than 3.1 to deliver the same payload at 270 nautical miles as the EOS. As shown in the previous figure, an 80,000-pound (36,200-kg) capacity space tug fully loaded has an efficiency coefficient of 4 and would deliver a net payload of about 27,600 pounds (12,500 kg) using a large crew module. For this reason, it is concluded that large space tugs should not be fully loaded in accomplishing this mission.

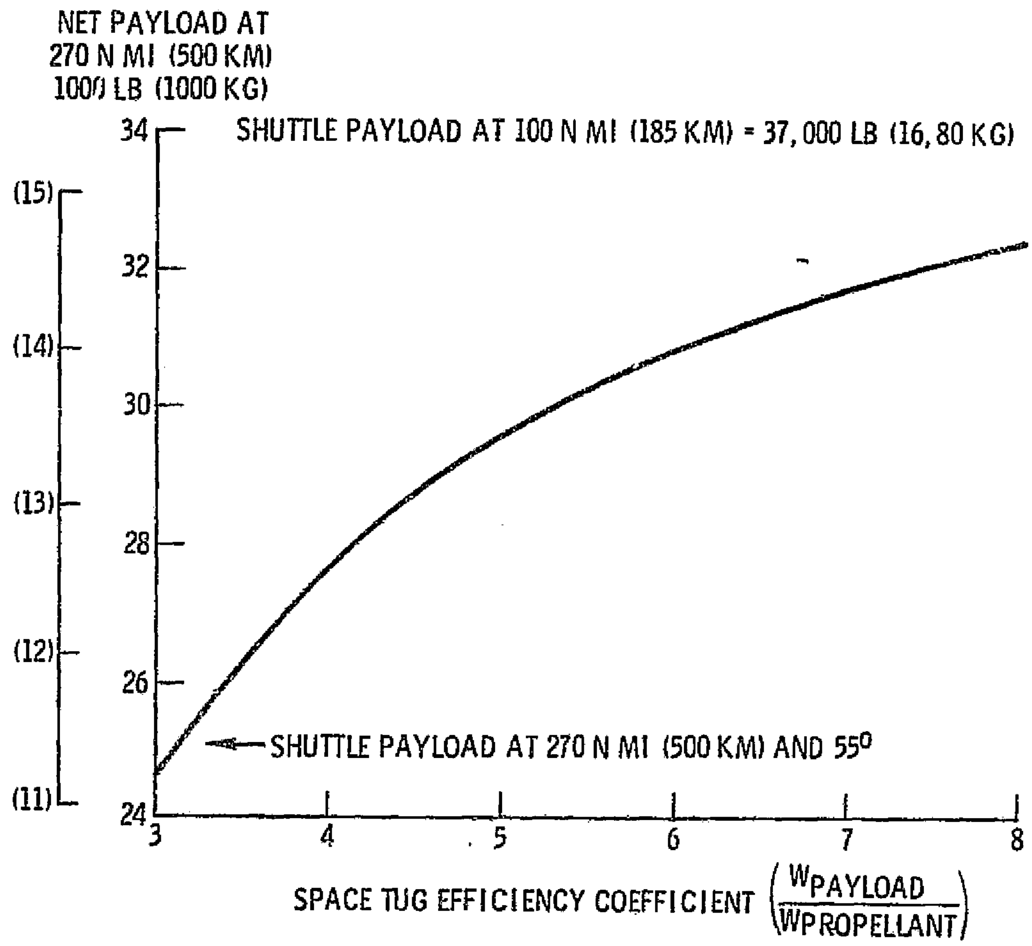


Figure 57. Payload Transfer Tradeoff

When off-loaded for a single mission, the 80,000 pounds (36,200 kg) propellant capacity tug with a large crew module has an efficiency coefficient of 6.1 and it delivers about 31,000 pounds (14,100 kg) round trip. A tug optimized for one round trip and operating in an unmanned mode has an efficiency coefficient of 7.9 and delivers about 32,400 pounds (14,700 kg) round trip, a 30 percent increase over that deliverable by the EOS.

Most operational studies of space station experiment modules have been conducted under the assumption that the space tug does not exist to aid in their placement and maintenance. As a result, these studies have led to the definition of a requirement for propulsive experiment modules. The operational approach suggested in the Phase A Experiment Module Concepts Study (NAS8-25051) was to initially place the experiment module in an orbit very near the space station, but with a slightly lower perigee. The module then

moved downward and rearward relative to the space station until its separation distance was about 400 nautical miles (740 km). An impulse was then applied to raise the apogee above the space station orbit from which it moves downward and toward the space station. The experiment module is then recovered and serviced.

This operational approach was modified to make it compatible with the utilization of a space tug and to eliminate the requirement for the application of an impulse by the experiment module (the experiment module would then only require attitude stabilization). In the revised operational mode, the experiment module would be placed by the space tug at some altitude above the space station and to the rear of the space station as shown in Figure 58 [e.g., 0.4 nautical miles (0.74 km) above the space station and 500 nautical miles (925 km) to the rear]. By lowering the perigee of the orbit below the space station orbit, the experiment module decays downward and toward the space station between servicing periods. The space tug is employed to retrieve the experiment module when it is close to the space station or directly service it. This process is repeated regularly with each of the experiment modules.

A trade-off was conducted to determine the optimum placement time, considering propellant required for the phasing orbits and expenditure of propellants for power and boiloff. Figure 58 shows total propellant required as a function of total mission time. These data indicate that a minimum propelllant expenditure of 280 pounds (130 kg) occurs at about 23-hours mission duration.

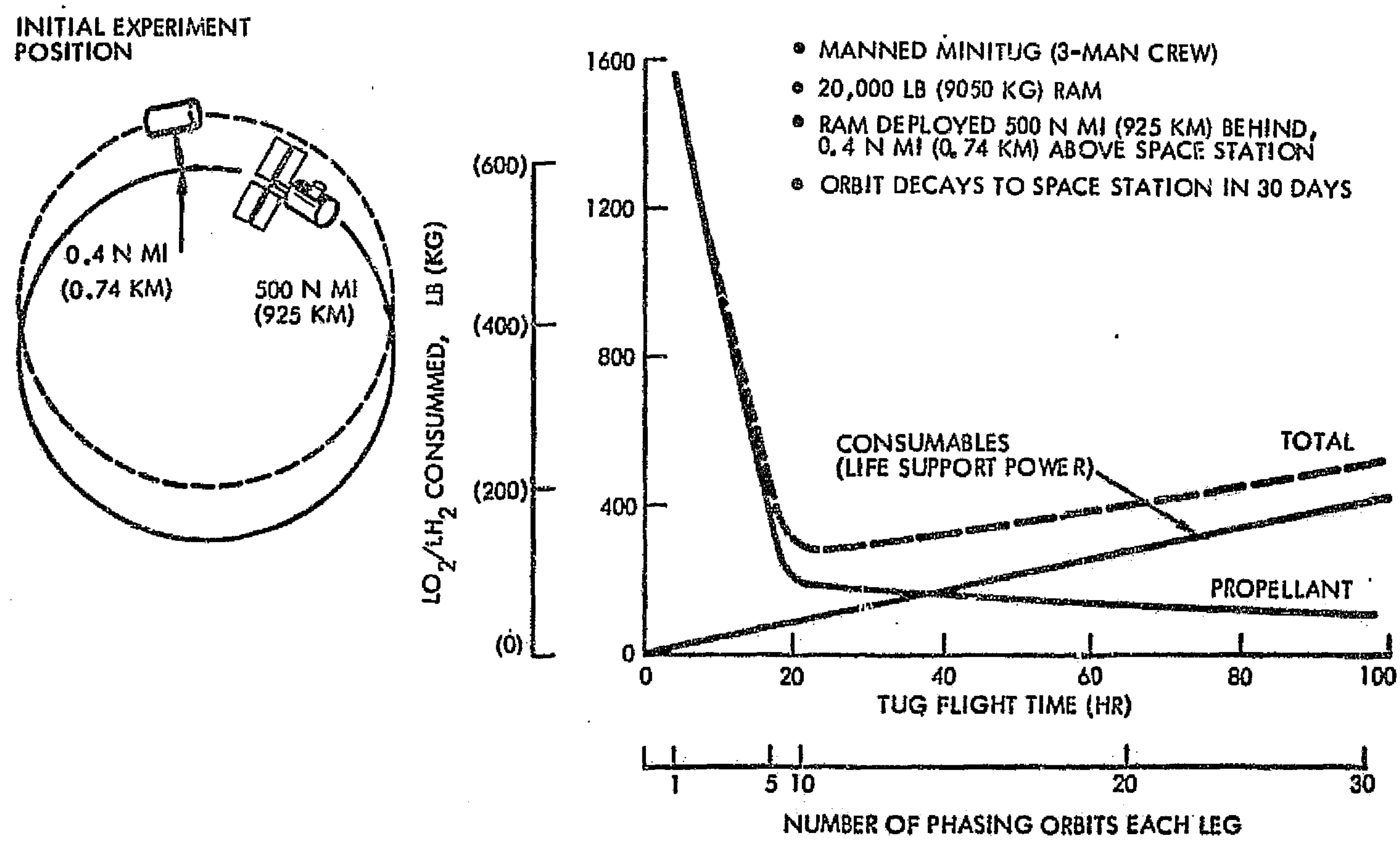


Figure 58. Space Tug Space Station Experiment Deployment Mission

The result of using the space tug for these operations is to simplify the basic requirements of the experiment module guidance and control system which would be necessary for each module if propulsive orbital corrections are made. The placement of the satellites by the tug requires only a modest expenditure of propellants.

If payload is transferred by the space tug between 100 nautical miles (185 km) and 270 nautical miles (500 km), the earth orbital shuttle will have about 25,000 pounds (11,300 kg) of propellant remaining in the orbital maneuvering system (OMS). Figure 59 shows the propellant required by the space tug in accomplishing all of the designated space station support missions (including payload transfer) and the amount of propellant each year available from the OMS system assuming a 100 nautical mile (185 km) EOS orbital altitude.

During the first few years of the space station program, sufficient OMS propellant is available to accomplish all of the tug missions. During the latter years of the program (space base), a large excess of propellants exist. The size of the excess suggests that planetary injection missions be launched from the space station rather than from 28.5 degrees, thus utilizing the excess. Additionally, because of the large amount of propellant in the OMS, a tug utilizing this resource should have a capacity greater

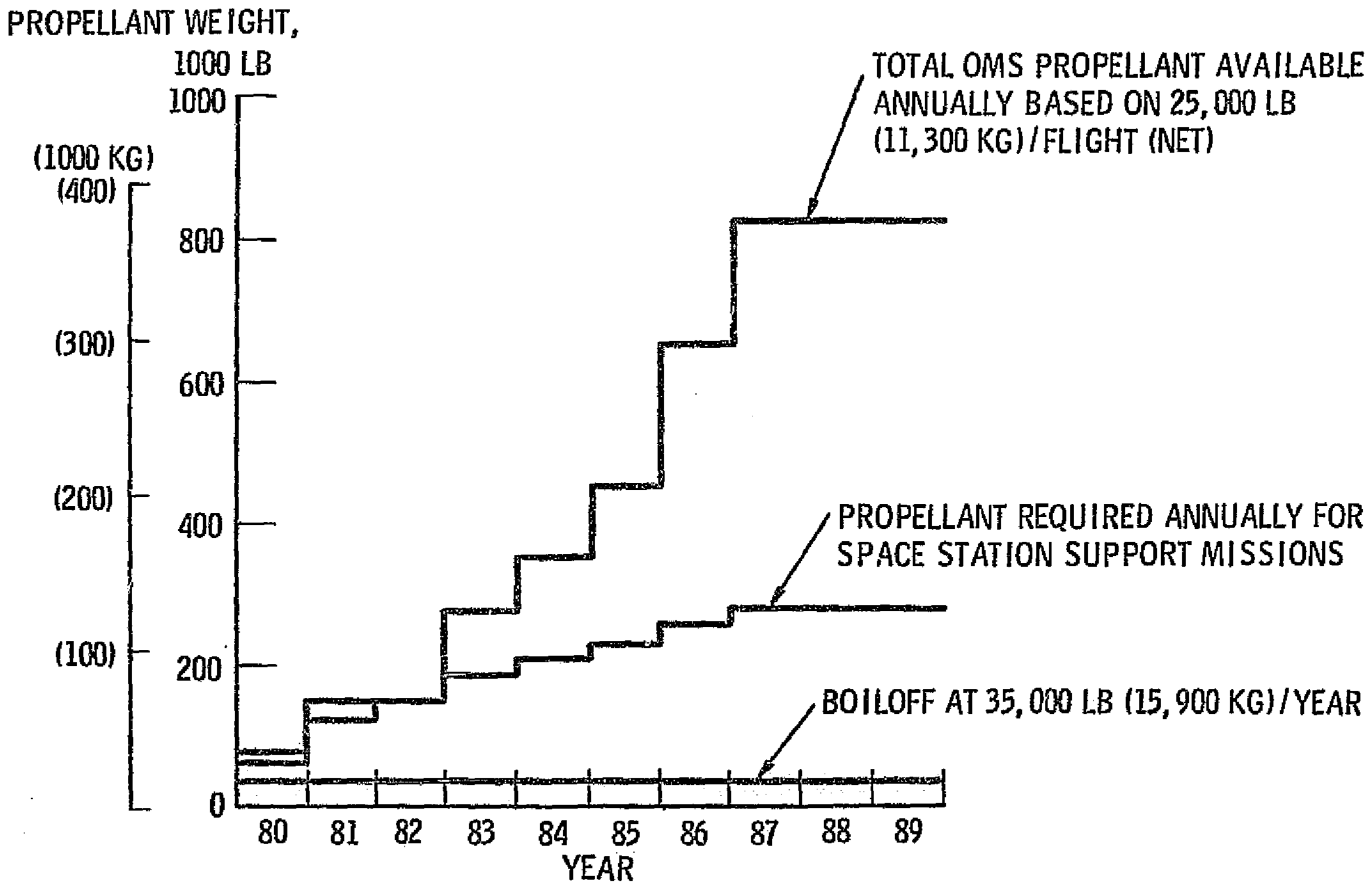


Figure 59. Comparison of Annual Space Station Propellant Requirements and Annual OMS Propellant Availability (Concept 1)

than 25,000 pounds (11,300 kg). This implies the need for tugs with large propellant capacities and is different from the result obtained if mission operations do not consider the OMS propellant [the required capacity would have been about 5000 to 10,000 pounds (2270 to 4540 kg)].

In order to meet the operational requirements of the space station, the space tug needs to be space based. In this mode, the payload transfer mission is more efficiently accomplished because the tug would otherwise have to be a part of the payload during ascent to orbit. Because of the relative frequency of placement, servicing, and maintenance of EOSS experiment modules, space basing is necessary to meet the possible irregular scheduling. Additionally if two space tugs are always on orbit at the space station (one on standby) additional safety is provided for EOSS personnel.

The space tug provides a life boat for rapidly carrying EOSS personnel away from the space station in the event of a major time dependent occurrence. It also provides rescue over a large range of orbital inclinations away from the space station. Considering phasing requirements for the EOS, the tug could allow the shuttle to ascend to orbit for rescue in a much shorter period of time, the space tug making the necessary plane change and phasing maneuvers.

Lunar Missions

The primary purpose of the tug in the lunar mission area is to provide logistics support between a low lunar orbit and the lunar surface and to provide the capability of supporting 4 men for missions up to 28 days on the lunar surface. No other systems have been considered for this purpose.

Because of its inherent capability, the space tug can also perform rescue and abort missions under extreme circumstances. It inherently has the capability with a crew module for (1) direct abort from the lunar surface to low earth orbit, (2) abort from lunar orbit to low earth orbit, (3) plane changes of up to 90 degrees with return to a lunar space station, (4) surface rescue from an orbiting lunar space station with plane changes up to 20 degrees, and (5) abort from the lunar surface to lunar orbit.

In addition to providing manned and unmanned lunar landing capability from low lunar orbit to lunar surface, the space tug also provides a stage that can be used in conjunction with the translunar shuttle to improve overall system efficiency. Figure 60 illustrates the capability of the space tug when used in conjunction with the reusable nuclear shuttle (RNS) as an earth-based retriever or refueler stage. In this mode, the RNS initiates its mission in low earth orbit, delivers a payload to lunar orbit, and returns to an elliptical earth orbit. The space tug, stationed in a coplanar low earth orbit, gets

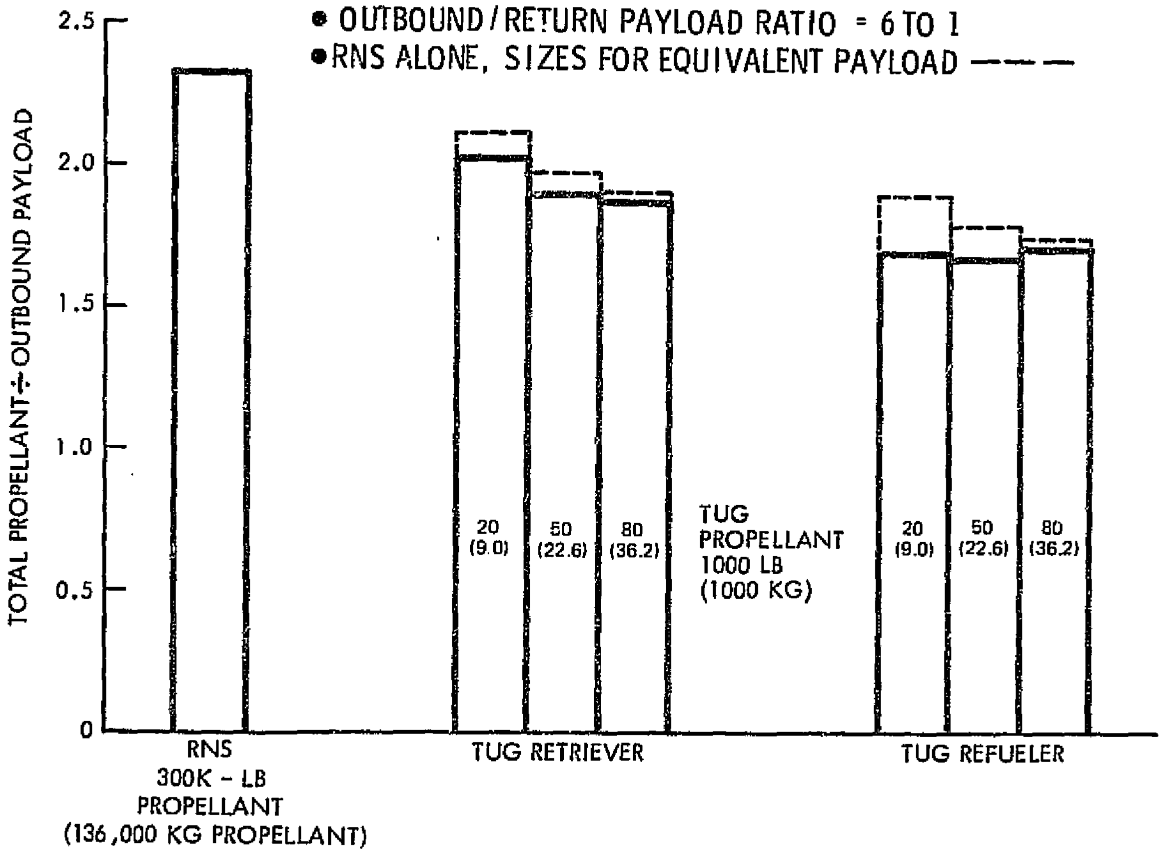


Figure 60. Comparison of RNS/Tug Flight Modes

into an elliptical orbit coincident with the RNS and accomplishes a rendezvous. In the retriever mode, the space tug attaches itself to the RNS and returns the RNS to low earth orbit utilizing the space tug propulsion system. In the refueler mode, the tug carries sufficient liquid hydrogen to the RNS for refueling to allow the RNS to propel itself and the tug back to low earth orbit. As shown, either space tug mode decreases the propellant to outbound propellant ratio as compared to use of the RNS alone to accomplish the mission. The retriever mode decreases this ratio by about 22 percent and the refueler mode decreases this ratio by about 37 percent. Comparison of these tug/RNS modes to an RNS alone, resized for an equivalent payload capability indicates considerably less reduction in the propellant to payload ratio.

Because the chemical translunar shuttle has a lower specific impulse than RNS, it would be expected that use of the tug in conjunction with the chemical shuttle would lead to even greater gains in efficiency. Table 15 shows the effect on the payload to propellant ratio of using a tug containing 60,000 pound (27,200 kg) of propellant as a second stage on a chemical translunar shuttle containing 540,000 pounds (245,000 kg) of propellant and on an SIVB size stage containing 230,000 pounds (105,000 kg) of propellant. Two space tug modes are shown, both utilizing the space tug as a second stage. In the first mode, the shuttle propels itself, the tug, and payload out

Table 15. Translunar Chemical Shuttle/Tug Mission Efficiency

	SINGLE STAGE VEHICLES			TWO STAGE VEHICLES ②			
						TUG REFUELED IN LUNAR ORBIT	
	RNS	CTS	SIVB	CTS + TUG	SIVB + TUG	CTS + TUG	SIVB + TUG
OUTBOUND PAYLOAD WITH 20,000-LB (9050 KG) RETURN, LB (KG)	135,000 (61,000)	92,000 (41,600)	5000 (2300)	100,000 (45,400)	33,000 (15,000)	210,000 (95,000)	92,000 (41,700)
PROPELLANT USED, ③ LB (KG)	305,000 (137,000)	540,000 (245,000)	230,000 (105,000)	600,000 (272,000)	290,000 (131,000)	644,000 (292,000)	334,000 (151,000)
PAYLOAD TO PRO- ① PELLANT RATIO	0.442	0.170	0.022	0.167	0.114	0.326	0.276

NOTES

① OUTBOUND PAYLOAD ONLY
② SLING SHOT MODE
③ SPACE TUG PROPELLANT WEIGHT = 60,000 LB (27,000 KG)

of a low earth orbit and into an elliptical lunar orbit where staging occurs. The shuttle returns by itself to low earth orbit while the tug delivers the payload to lunar orbit and then returns to earth orbit with return payload. In the second mode (tug refueled in lunar orbit), the shuttle propels itself, the tug and payload out of low earth orbit and into either a highly elliptical earth orbit or highly elliptical lunar orbit. The tug stages and uses all of its propellent to place the payload into lunar orbit. The tug refuels from the payload with sufficient fuel to return to a low earth orbit with the required payload.

Because the tug is small when compared to the shuttle, the refueling mode shows considerably greater benefits. It increases the value of the payload to propellant ratio from 0.170 for the chemical translunar shuttle (CTS) alone to 0.326 and from 0.022 for the S-IVB size stage alone to 0.276. When this mode is used, the performance of the chemical stages approaches the performance of the RNS when used alone as a single stage. Use of the tug as a second stage also improves mission safety since the tug can be used as an escape vehicle should a first-stage malfunction occur.

Geosynchronous Mission

The prime competitive approaches for conducting the geosynchronous missions include the use of expendable LO_2/LH_2 stages or the use of a

reusable space tug. In the next several paragraphs, the primary comparison issues will be discussed. These include economic comparisons of these systems for insertion of payloads up to 10,000 pounds (4,540 kg) as well as the economic aspects of payload retrieval from geosynchronous conditions. Additionally, the characteristics of the earth orbital shuttle, including payload weight capability and bay size will be considered in making the comparisons.

As will be explained subsequently, the use of the EOS orbital maneuvering system propellants also has a significant effect on economics. These LO_2/LH_2 propellants [up to 25,000 pounds (11,300 kg)] would be available on orbit for transfer to the space tug for a normal EOS mission since they are contingency propellants required for an abort to orbit in the event of an engine failure in the second stage during ascent. In essence, the ability to utilize these propellants is equivalent to increasing the payload capability of the earth orbital shuttle by 25,000 pounds (11,300 kg).

The first area of comparison between reusable and expendable systems is the economics of payload insertion at geosynchronous equatorial conditions. Figure 61 shows the cost per mission for LO_2/LH_2 and N_2O_4/A-50 expendable systems and for a ground and space-based reusable tug. Because of the potential variations in EOS capability, EOS capability is shown as a parametric value. The break points shown as a function of EOS capability

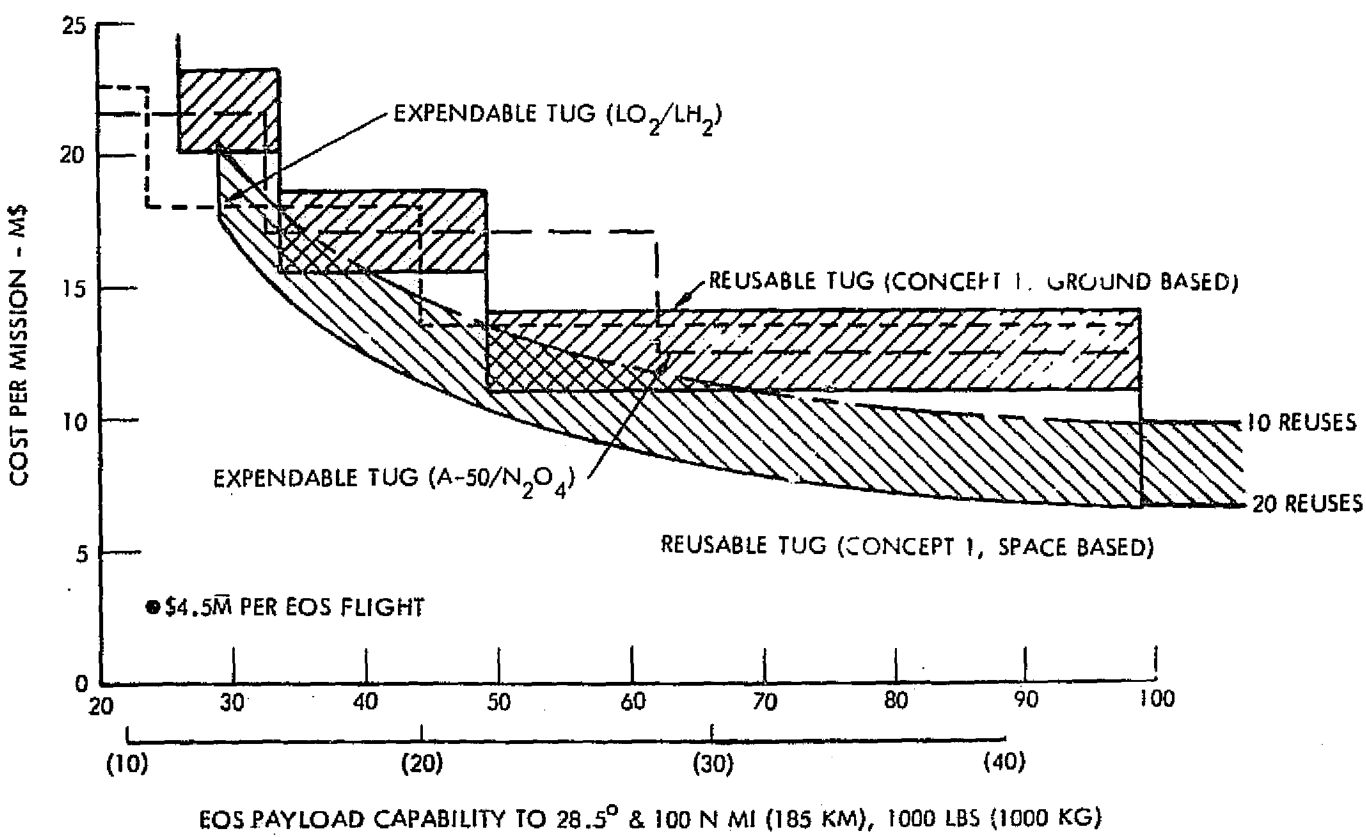


Figure 61. Comparison of Geosynchronous Equatorial Mission Costs of Reusable and Expendable Systems

for the ground-based concepts correspond to an integral number of EOS flights required as EOS capability increases. For the concept 1 baseline design, about a 99,000 pound (44,900 kg) EOS payload capability is required for a single EOS launch. The upper and lower bounds shown for concept 1 are related to 10 and 20 reuses, respectively.

This figure indicates that the reusable and expendable concepts have comparable mission costs at low values of EOS capability and that the effect of increasing EOS capability is to considerably reduce the mission cost for the reusable concept. As shown, the costs of the expendable concepts are comparable to each other, but the LO_2/LH_2 stage requires only a 45,000 pound (20,400 kg) capability for a single EOS flight mission as compared to a 62,000 pound (28,100 kg) capability for the N_2O_4/A-50 stage. These data indicate that the reusable system economics are considerably improved with a large EOS payload capability.

A reusable space tug designed to insert 10,000 pounds (4,540 kg) of payload at geosynchronous equatorial conditions also has the capability of retrieving large payloads. For example, concept 1 can retrieve about 3900 pounds (1,770 kg) of payload operating as a single stage. Figure 62 shows the cost per pound of retrieving payloads as a function of payload weight for three assumed operational modes:

1. No payload out-bound and propellant off loaded

2. Equal outbound and inbound payloads and propellant offloaded

3. Payload outbound offloaded and a full propellant load

The lower bound curve is not the most likely situation, since it assumes that the full outbound tug capacity can be utilized. The upper bound curve is not considered to be an effective operational mode. The equal outbound and inbound curve would correspond to a mode wherein a like payload is delivered at the same time a malfunctioning payload is retrieved. This mode is considered to be the most likely to occur. The maximum capability of concept 1 for this mode is about 2,900 pounds (1,302 kg).

A brief analysis of satellite malfunction rates at times soon after their insertion was made, and it was estimated that the failure rate was at least 5 percent and perhaps as high as 10 percent. An analysis of the cost per pound of satellites (Surveyor, Nimbus, Orbiter, Mariner II and IV, OSO, OGO, BIO, Ranger, and OAO) indicated a range between 20,000 and 90,000 dollars per pound (44,000 and 198,000 dollars per kg). The lower bound of these data, a nominal satellite weight of 2000 pounds (9,050 kg), a failure rate of 5 percent, and a retrieval cost of $5,000 dollars per pound

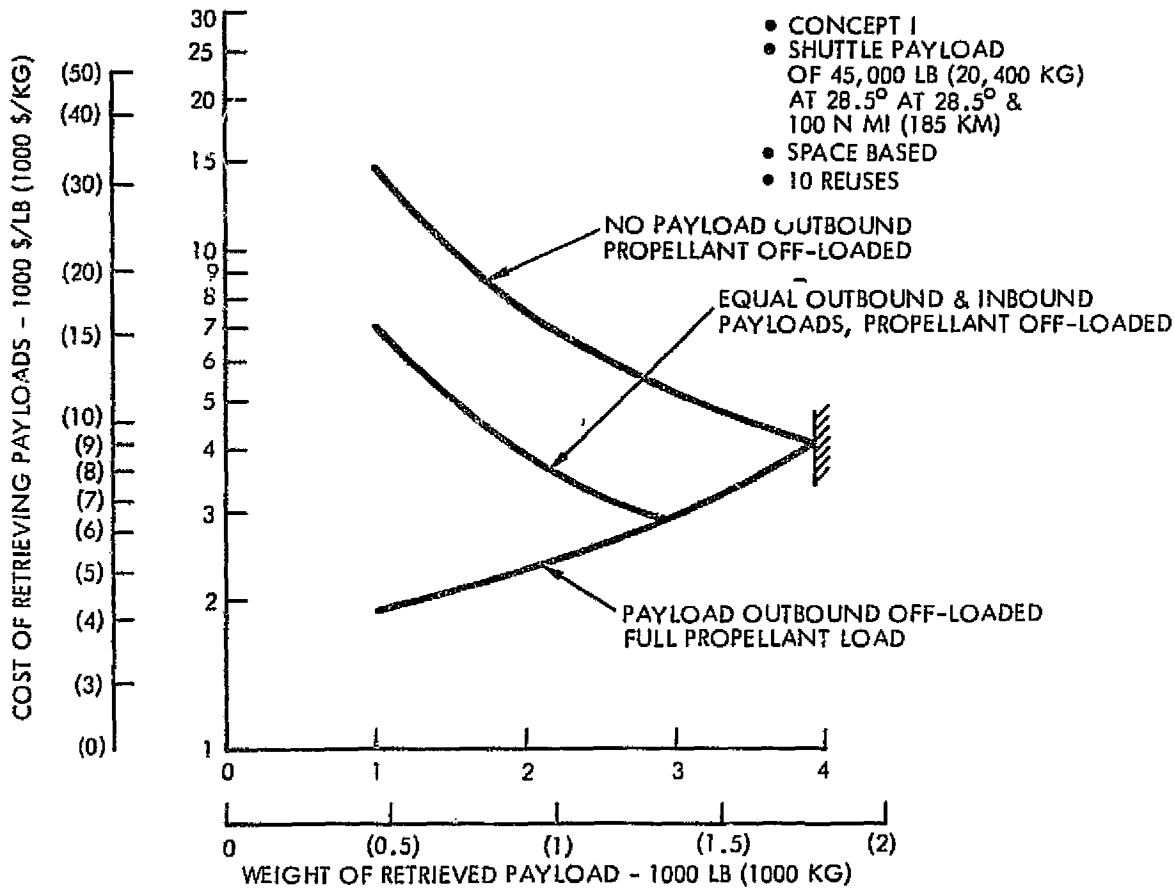


Figure 62. Cost of Retrieving Payloads From Geosynchronous Equatorial Orbit

(11,000 dollars per kg) were assumed to determine the cost saving for the baseline NASA geosynchronous program. This nominal cost saving and parametric data relating to payload retrieval savings are shown on Figure 63.

A comparison of the total ten year NASA geosynchronous mission costs for space-based reusable and expendable systems are shown in Figure 64. A shuttle payload capability of 45,000 pounds (20,400 kg) at 28.5 degrees and 100 nautical miles (185 km) was assumed for calculating the reusable concept propellant resupply costs. A comparison of the baseline design with maximum autonomy to the expendable system indicates comparable program costs for a tug that is reused 20 times. If 25,000 pounds (11,400 kg) of orbital maneuvering system propellant are utilized by the reusable system (this essentially increases the EOS payload capability by the OMS propellant weight), the reusable system cost drops from \$550 to \$370 million. Inclusion of the cost savings potentially available from retrieval of malfunctioning geosynchronous payloads reduces the program cost to \$120 million.

Figure 65 compares the geosynchronous program costs of expendable concepts and three versions of a ground based reusable space tug. The earth orbital shuttle payload capability is assumed to be consistent with the required gross weight shown for each concept. This figure indicates that

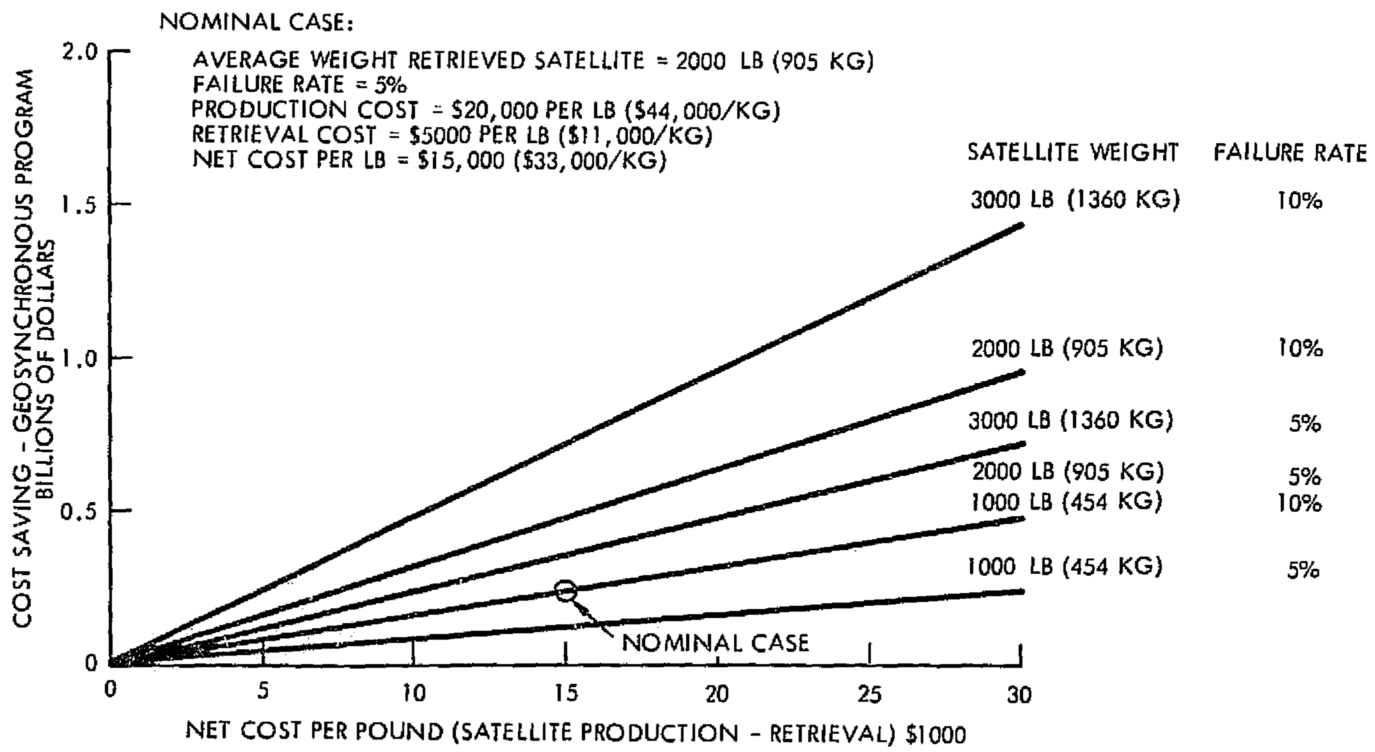


Figure 63. Parametric Determination of Cost Savings From Retrieval of Malfunctioning Geosynchronous Satellites (Concept 1)

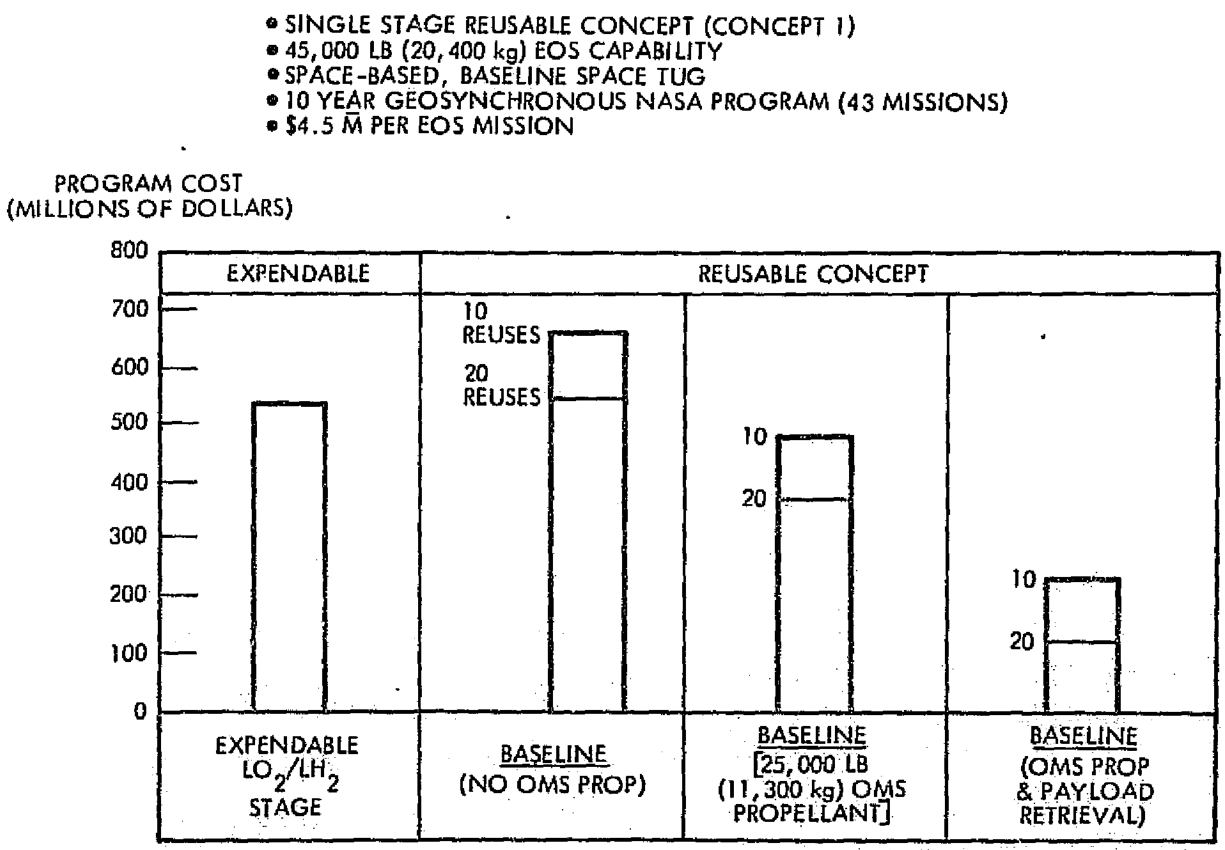


Figure 64. Comparative Cost of Geosynchronous Mission for Space-Based Reusable and Expendable Concepts

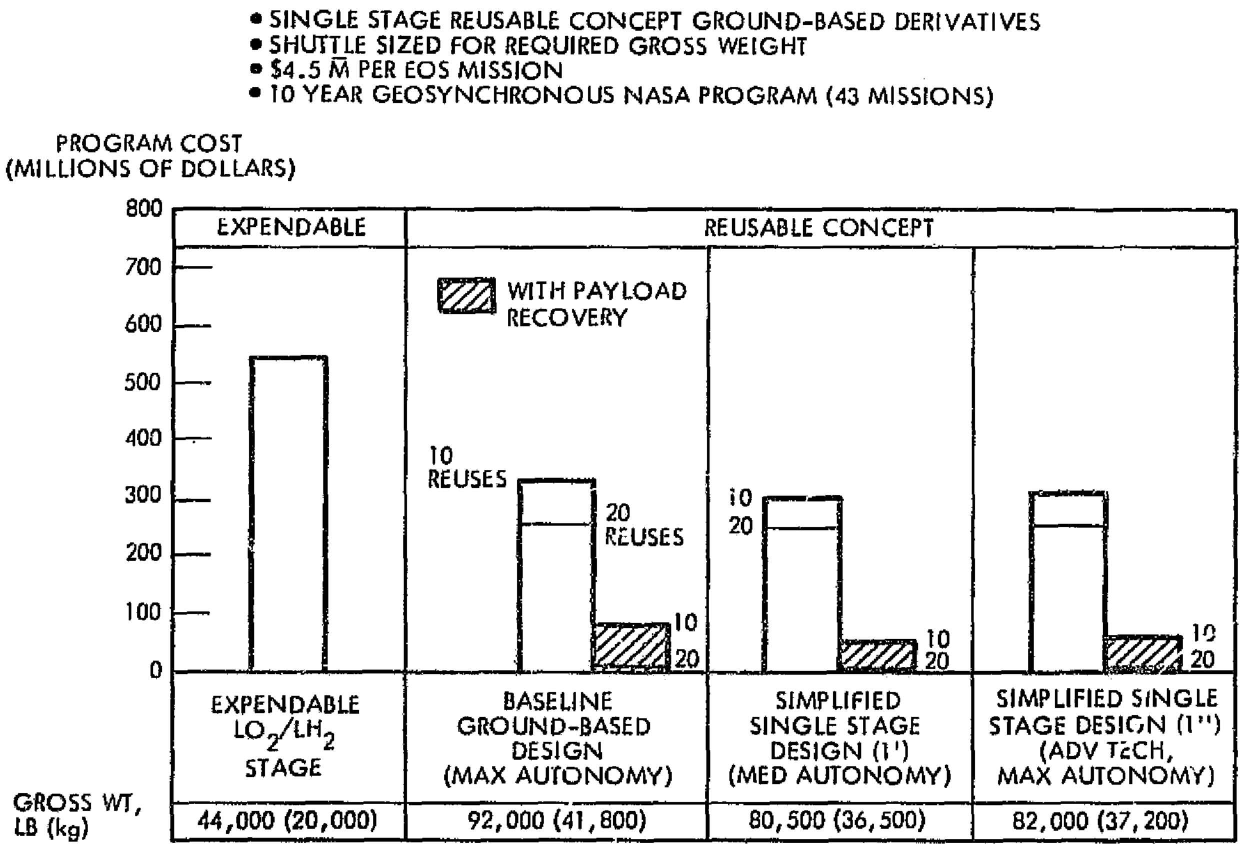


Figure 65. Comparative Cost of Geosynchronous Mission for Ground-Based Reusable and Expendable Concepts

the ground-based reusable systems show a substantial program cost reduction when compared to the expendable system. When the estimated cost saving for payload retrieval is included, the program cost is reduced nearly to zero. All of the reusable concepts have comparable program costs, but the required EOS payload capability varies from 80,500 pounds (36,500 kg) to 92,000 pounds (41,800 kg) as the design is varied, assuming that the EOS orbital maneuvering system propellants are not utilized. Required EOS capability would be 25,000 pounds (11,300 kg) less if the OMS propellants are utilized.

The above data show that the space tug can accomplish the geosynchronous mission on a basis at least comparable to expendable stages when a 45,000 pound (20,400 kg) EOS capability at 28.5 degrees and 100 nautical miles (185 km) is assumed. At this size shuttle capacity, inclusion of payload retrieval savings and use of the OMS propellants significantly reduces the reusable system cost. Increasing the EOS capability to allow single EOS flight ground based space tug missions leads to even greater economic benefits.

CONCLUSIONS

As a result of the reusable space tug study, several significant conclusions have been reached. These conclusions are summarized in the following paragraphs, which discuss (1) the feasibility of a single modular space tug concept, (2) a comparison of the space tug with other concepts, (3) space tug interfaces with other systems, (4) space tug module interfaces, and (5) technology implications.

FEASIBILITY OF SINGLE MODULAR CONCEPT

As a result of this study, it was determined that the performance requirements of the geosynchronous equatorial mission provided the main driver for sizing of the space tug propulsion module. Several concepts were studied during Phase I and three of these concepts were selected for a more detailed analysis during the second phase of the study. All of these were sized by the geosynchronous mission.

When applied to accomplish other earth orbital missions, the selected concepts were found to provide satisfactory performance capability. Even though the large single stage reusable concept was oversized for the low earth orbit support missions, off-loading propellants in the large stage lead to performance characteristics 15 percent less than for an optimized stage.

When these concepts were applied to the lunar landing mission, it was found that the crew module would provide improved functional characteristics if it were placed at the bottom of the stage rather than on the upper portion of the stage as it is in orbital operations. This tends to force the engines outboard to clear the crew module.

As a result, it was concluded that a multipurpose space tug is economically feasible for application to both the high and low performance earth orbital missions. This design would, however, require a block change (like Apollo block 1 to block 2) for accomplishment of lunar missions.

COMPARISON OF SPACE TUG AND OTHER CONCEPTS

A comparison of the space tug was made with other, potentially competitive concepts in each of the prime mission areas (geosynchronous, space station support, and lunar). In the lunar mission area, no competitive concepts have been considered for the lunar orbit to surface logistics missions.

When logistics support between earth and lunar orbit is considered, it was found that the tug, functioning in conjunction with a nuclear or chemical cislunar shuttle can significantly improve payload logistics efficiency. In these missions, the tug is used as an earth retrieval stage or a second stage on the cislunar shuttle. When used as an earth retrieval stage for the nuclear shuttle, a 37 percent increase in payload to propellant ratio occurs. As a second stage on a large chemical (LO_2/LH_2) stage, the tug doubles the payload to propellant ratio.

In analyzing the space station support missions, it was found that the space tug can accomplish all of the required support functions: payload transfer and experiment module placement, retrieval, and servicing.

In accomplishing payload transfer missions, the space tug can improve net delivered payload to the space station by at least 30 percent. In this case, the tug delivers payload between the space station at 270 nautical miles (500 km) and the EOS in a 100 nautical miles (185 km) parking orbit.

The space tug can also emplace and retrieve the space station experiment modules using only 280 pounds (130 kg) each time. This capability allows simplification of the experiment modules by relieving them of the need for propulsive maneuvers and rendezvous and docking. One central vehicle, the tug, provides these functions, when necessary, rather than requiring this capability in each of the experiment modules.

It was found that a sufficient quantity of orbital maneuvering system (OMS) propellants remain in the shuttle when parked at 100 nautical miles to provide all of the propellant required annually by the tug to perform all of the space station missions. When a space base is in operation, considerable propellant excess exists [550,000 pounds/year (228,000 kg/year)] suggesting that unmanned planetary missions be launched from the space station using a reusable tug and the excess propellants.

Because of the numerous support missions in the space station area, space basing of the tug is suggested. The space-based tug also provides abort and rescue capability at the space station and in the overall low earth orbit area.

Considerable effort was placed on the analysis of the geosynchronous payload emplacement mission and a comparison of reusable space tug concepts with concepts designed for expenditure on these missions. These comparisons indicated that a space based, fully autonomous space tug was at least economically comparable with an expendable system. As in the space station mission area, the tug can utilize the unused shuttle orbital maneuvering system propellants to improve mission efficiency. When utilization of

OMS propellant and potential cost savings resulting from space tug payload retrieval are considered, the space-based space tug concept is considerably more efficient than an expendable vehicle approach (the total 10-year program cost is reduced from $550 million for the expendable to $120 million for the Space Tug). Ground basing of the tug to operate as a third stage of the shuttle improves geosynchronous mission economics even more (the total 10-year program cost is reduced to nearly zero when ground basing and payload recovery benefits are considered).

SPACE TUG INTERFACES WITH OTHER SYSTEMS

In accomplishing the broad range of missions, the space tug must interface with all of the systems considered in the integrated program plan. The character of these interfaces is described in the following sections.

Earth Orbital Shuttle

The earth orbital shuttle is the key interfacing system for the space tug, particularly when use of the tug as a ground-based third stage is considered. In this case, not only are the payload bay dimensions important, but the payload capacity of the shuttles closely constrains the space tug design.

The current 15 foot (4.6 m) bay diameter is acceptable, but a smaller diameter would lead to increased tug length. Greater tug length would impact the lunar landing concept which is best in a low profile configuration. The current 60 foot (18.3 m) bay restriction is marginal and may reduce the potential for multiple geosynchronous payload injection missions. Increases in both length and diameter would relieve tug design constraints. A diameter increase would be most beneficial.

A shuttle sized to carry 45,000 pounds (20,400 kg) at 100 nautical miles (185 km) and 28.5 degrees does not allow the conduct of ground-based geosynchronous missions unless complex multiple-launch missions are staged. For the design concepts considered in this study, an EOS capability of between 80,000 and 99,000 pounds (36,300 and 44,900 kg) would be required for ground-basing if orbital maneuvering system (OMS) propellant sharing is not used. Use of OMS propellant sharing reduces the EOS payload capability requirement to between 55,000 and 74,000 pounds (25,000 and 33,600 kg) assuming that 25,000 pounds (11,200 kg) of OMS proepllants are normally available for sharing.

OMS propellant sharing introduces another interface between the tug and the EOS. The LO_2 and LH_2 systems of the tug and the shuttle OMS would have to be plumbed together during ascent to allow sharing of the propellants either for EOS abort to orbit or utilization in the space tug for mission accomplishment.

The EOS docking and payload handling scheme also affects the tug significantly. The so-called "cherry-picker" manipulator scheme appears best suited for the tug. It allows the use of a single engine concept without the need for active docking avionic systems and docking mechanisms. This reduces the tug gro s weight by about 6000 pounds (2,700 kg).

Other interfaces with the shuttle include provisions for propellant venting, electrical interconnects for tug status monitoring by the EOS, and an active EOS role in commanding tug docking (should docking be required).

Space Station

While the space tug is conducting missions in the vicinity of the space station, it is assumed that the space station would have the active role in command. Upon docking of the tug with the EOSS, the space station would also have control override. While docked to the space station for extended periods, it would be desirable or the EOSS to provide compatible power to reduce tug consummables. All tugs in operation at the space station would be required to have docking gear compatible with the space station. Space station servicing of the tug would be considered to be minimized by the tug to eliminate the need for special facilities at the space station or EVA.

Space tug interfaces with the orbiting lunar space station are assumed to be similar to the EOSS. However, prior to lunar surface base operation, it is assumed that the lunar space station would be the control center for surface operations. It would also provide the capability for loading or unloading of lunar cargo.

Lunar Surface Base

When the lunar surface base becomes operational, tug operations to the surface will become routine. To aid in these operations, it is desirable that a prepared landing area with beacons as landing aids be provided. The surface base should also provide the mobility devices necessary to transfer cargo and personnel from the tug. Long-time quiescent status of the tug on the lunar surface would require electrical power from the surface base, and, perhaps, proepllant reliquification provisions. Interconnects for tug status monitoring would also be desirable.

Cislunar Shuttle

The space tug will be required to provide translational and perhaps rotational control of the large chemical or nuclear translunar shuttles. Compatible docking gear will be required for these operations. If the tug is used as a second stage, docking between the tug and CLS will also be required. Use of the crew module with the nuclear shuttle will require electrical and fluid interconnects similar to those required between the tug IM and PM and the crew module. Additional protective shielding of the crew module from the nuclear environment will be necessary.

The tug may also be employed to remove and dispose of the nuclear shuttle main engine. This operation will require special manipulators. These operations are being studied under reusable nuclear shuttle contracts.

Payloads

If payloads are to be integrated on orbit with the tug, a compatible docking gear will be necessary. This study indicated that large neuter docking gear are undesirable for payload/tug integration because of excessive weight penalties. A more appropriate approach is provided by the Apollo-type docking gear. When payload retrieval is considered, the best mode of retrieval would be in a hard-docked configuration.

SPACE TUG MODULE INTERFACES

As shown previously, the interfaces between space tug modules include not only mechanical connections, but also fluid and electrical connections. They result in a relatively complex mating operations if mating on orbit is necessary. For this reason, it would be highly desirable to avoid space integration of the crew, propulsion, and intelligence modules. Ground integration would allow an integrated checkout of the system prior to placing the tug in orbit.

The lunar landing mission poses special interface problems. The more desirable aft crew module location requires the relocation of interfacing connections. It also results in outboard and multiple engine geometry. Integration in orbit of the landing legs and cargo pods would be necessary. For the most part, integration of the landing legs and cargo pods require only mechanical matings.

TECHNOLOGY IMPLICATIONS

The baseline space tug system was constrained to maximize the use of earth orbital shuttle and space station technology. In the areas of cryogenic insulation, zero-g propellant behavior, and possibly engine technology, shuttle technology appears to offer the major technology required by the space tug. Assuming that the shuttle orbital maneuvering system employs a new high-chamber pressure engine, the space tug main engines may closely match their specification. If the space tug has two to four engines, the thrust levels may match adequately. Close coordination of the tug and OMS engine development may lead to compatibility. Potential areas of difference include turbomachinery cycles and nozzle area ratio. For lunar missions, throttling will be required.

A brief analysis of advanced avionics (advanced beyond shuttle and space station) indicated that potentially large inert weight savings may be realized by utilizing the improvements in the state-of-the-art of sensors, guidance and navigation equipment, and computer equipment. These inert weight savings in turn lead to significant reductions in tug gross weight and program cost.

RECOMMENDATIONS

The following recommendations address themselves to space tug approaches and further space tug related effort.

PROPULSION MODULE APPROACHES

Of the three propulsion module approaches studied during Phase II, the most attractive concept was concept 1. This concept was economically comparable to other concepts, had the best growth potential, and was operationally simple. It was the only concept which had only one staging relationship for all missions (single stage).

Concept 11, which utilizes a 1-1/2-stage principle for high energy missions appears to have certain special advantages. The small propulsion module by itself is adequate for the low earth orbit missions and can be put into the shuttle bay with large payloads. It also has the lowest gross weight for the geosynchronous equatorial mission, which may be advantageous, dependent on EOS payload capability. Economic disadvantages resulting from tank set expenditures during high energy missions were offset by its performance in other areas not requiring expenditure.

The two-stage concept (concept 5) was economically comparable to other concepts, but was found to be excessive in length. Because of its two-stage operation for high energy missions, overall operations were found to be complex.

Based on the data obtained in this study, it is recommended that Concepts 1 and 11 continue to be pursued in future studies.

INTELLIGENCE MODULE APPROACHES

Three intelligence module approaches were considered: totally modularized, partially modularized, and integrated. Total modularization allowed use of the IM separate from the propulsion module. In this application, it is necessary to provide a small module containing LO_2/LH_2 to provide adequate expendables for practical use. Such a configuration, along with the crew module, may be used for low earth orbit ministation missions. It should be noted that the small propulsion module of concept 11 has about the right capacity for this type of mission. Therefore, integration of the IM components into the small concept 11 propulsion module would still allow the ministation type missions.

The weight decreases resulting from partial or total integration of the IM into the propulsion module result in significant gross weight reductions, particularly for concept 1 [total integration reduces gross weight by 3600 pounds (1,600 kg) and partial integration reduces gross weight by 1800 pounds (800 kg).] Integration of electronic functions into a module (partially integrated IM) allows all of the fluid functions to be located in the stage and results in only electrical interfaces between the IM and PM. From a manufacturing, checkout, and refurbishment viewpoint, a partially integrated IM appears attractive.

At this point in the space tug program, a specific IM recommendation does not appear prudent. The choice is highly dependent upon propulsion module concept, on the payload capability of the shuttle, and upon the desirability of utilizing the IM for mini-station type missions.

CREW MODULE

In comparing the vertical cylinder and horizontal cylinder crew modules, it was found that both had similar functional characteristics when constrained by the EOS bay diameter. They also provided adequate volume for the 4-man 28-day lunar surface mission. The vertical cylinder crew module is recommended on the basis of ease of integration of this concept with other vertical cylindrical modules. By modifying internal arrangements, this same module can be used for low earth orbit support missions and can provide a rescue capability for up to 12 men.

RECOMMENDED FUTURE EFFORT

As a result of this study, several areas have been identified where additional effort would be beneficial. The most significant of these fall into the general categories of economic studies and operations and design studies.

Economic studies of payload retrieval, variations in tug design payload capability, and EOS orbital maneuvering system propellant utilization appear to be key elements of tug program economics. As shown, payload retrieval decreases the geosynchronous program cost by a large percent. Decreases in the space tug payload delivery capability at geosynchronous conditions from 10,000 pounds to lower values can have a significant effect on the ability to inject multiple payloads as well as to retrieve payloads. Use of EOS orbital maneuvering propellants significantly reduces propellant resupply cost for space based operation or, alternately, decreases the required EOS payload capability for ground-based operations.

Future design studies should be closely tied to the EOS studies to assure compatibility in the key interface areas, including the space tug integration into the bay, removal on orbit, and retrieval. Because of the significance of orbital maneuvering system propellant sharing, considerable design attention is required to assure tug/EOS compatibility. More detailed tug design studies are required to develop design data, not only in the shuttle interface areas, but also in the design of space tug systems. The influence of advanced avionics on tug performance and costs should be more critically investigated. Additionally, the influence of varying degrees of tug autonomy on support from other systems (shuttle, space station, ground tracking, etc.) should be studied to determine the feasi ility of utilizing other than a fully autonomous system.